

## Chapter IV: Technological Feasibility

### A. Feasibility of Tier 2 Exhaust Emission Standards for LDVs and LDTs

#### 1. NMOG and NO<sub>x</sub> Emissions from Gasoline-Fueled Vehicles

Emission control technology has evolved rapidly since the passing of the CAA Amendments of 1990. Emission standards applicable to 1990 model year vehicles required roughly 90 percent reductions in exhaust HC and CO emissions and a 75 percent reduction in NO<sub>x</sub> emissions compared to the uncontrolled emissions. Some vehicles currently in production show overall reductions in these three pollutants of more than 99 percent. These vehicles emissions are well below those necessary to meet the current federal Tier 1 and even California LEV standards.

A number of technological advances and breakthroughs have allowed these significant emission reductions to occur without the need for expensive, exotic equipment and fuels. For example, ARB originally projected that many vehicles would require electrically heated catalysts to meet their LEV program requirements. Today, no manufacturer is expected to use these devices to comply with the LEV program requirement. EPA projected that alternative fuels, such as methanol or natural gas, may be needed to meet these low emission levels. Today, while vehicles using these alternative fuels are capable of meeting the California LEV requirements, so are vehicles fueled with gasoline.

The most significant improvements which have facilitated these low emission levels have been to traditional catalysts, which now warm up very rapidly and are substantially more durable than past technology, and to fuel metering, which is more precise and accurate than previous systems. Improvements have also been made to base engine designs, which have resulted in lower engine-out emissions. Reduction of combustion chamber crevice volumes and oil consumption are examples of improvements to base engine designs.

Table IV-1 below lists specific types of emission controls which EPA projects will be needed in order for LDVs and LDTs to meet the proposed Tier 2 standards. It is important to point out that the use of all of the following technologies is not necessarily required to meet the proposed Tier 2 standards. The choices and combinations of technologies will depend on several factors, such as current engine-out emission levels, effectiveness of existing emission control systems, and individual manufacturer preferences. In some cases, such as projected increases in catalyst volume and precious metal loading, EPA believes that most, if not all, LDVs and LDTs will use the specified emission control technique.

**Table IV-1. Emission Control Hardware and Techniques  
Projected to Meet Proposed Tier 2 Vehicle Standards**

<i>Emission Control Technologies</i>	
Fast Light-Off Exhaust Gas Oxygen Sensor	Injection of Air into Exhaust
Universal Exhaust Gas Oxygen Sensor	Heat Optimized Exhaust Pipe
Retarded Spark Timing at Start-Up	Leak-Free Exhaust System
More Precise Fuel Control	Close-Coupled Catalyst
Faster Microprocessor	Improved Catalyst Washcoats
Individual Cylinder Air-Fuel Control	Increased Catalyst Volume and PGM Loading
Manifold with Low Thermal Capacity	Full Electronic Exhaust Gas Recirculation
Air-Assisted Fuel Injection	Engine Modifications

**a. Technology Description**

The following descriptions provide an overview of the latest technologies capable of reducing exhaust emissions. The descriptions will also discuss the state of development and current production usage of the various technologies. The technology descriptions are divided into four categories - base engine improvements, improved fuel control, improved fuel atomization, and improved catalyst performance.

*i. Base Engine Improvements*

There are several design techniques that can be used for reducing engine-out emissions, especially for HC and NO<sub>x</sub>. The main causes of excessive engine-out emissions are unburned HC's and high combustion temperatures for NO<sub>x</sub>. Methods for reducing engine-out HC emissions include the reduction of crevice volumes in the combustion chamber, reducing the combustion of lubricating oil in the combustion chamber and developing leak-free exhaust systems. Leak-free exhaust systems are considered to be base engine improvements because any modifications or changes made to the exhaust manifold can directly affect the design of the base engine. Base engine control strategies for reducing NO<sub>x</sub> include the use of "fast burn" combustion chamber designs, multiple valves with variable-valve timing, and exhaust gas recirculation.

*Combustion Chamber Design*

Unburned fuel can be trapped momentarily in crevice volumes (i.e., the space between the piston and cylinder wall) before being subsequently released. Since trapped and re-released fuel can increase engine-out HC, the reduction of crevice volumes is beneficial to emission performance. One way to reduce crevice volumes is to design pistons with reduced top “land heights” (The distance between the top of the piston and the first piston ring). The reduction of crevice volume is especially desirable for vehicles with larger displacement engines, since they typically produce greater levels of engine-out HC than smaller displacement engines.

Another cause of excess engine-out HC emissions is the combustion of lubricating oil that leaks into the combustion chamber, since heavier hydrocarbons in oil do not oxidize as readily as those in gasoline. Oil in the combustion chamber can also trap gaseous HC from the fuel and release it later unburned. In addition, some components in lubricating oil can poison the catalyst and reduce its effectiveness. To reduce oil consumption, vehicle manufacturers will tighten tolerances and improve the surface finishes of cylinders and pistons, improve piston ring design and material, and improve exhaust valve stem seals to prevent excessive leakage of lubricating oil into the combustion chamber.

As discussed above, engine-out NO<sub>x</sub> emissions result from high combustion temperatures. Therefore, the main control strategies for reducing engine-out NO<sub>x</sub> are designed to lower combustion temperature. The most promising techniques for reducing combustion temperatures, and thus engine-out NO<sub>x</sub> emissions, are the combination of increasing the rate of combustion, reducing spark advance, and adding a diluent to the air-fuel mixture, typically via exhaust gas recirculation (EGR). The rate of combustion can be increased by using “fast burn” combustion chamber designs. A fast burn combustion rate provides improved thermal efficiency and a greater tolerance for dilution from EGR resulting in better fuel economy and lower NO<sub>x</sub> emissions. There are numerous ways to design a fast burn combustion chamber. However, the most common approach is to induce turbulence into the combustion chamber which increases the surface area of the flame front and thereby increases the rate of combustion, and to locate the spark plug in the center of the combustion chamber. Locating the spark plug in the center of the combustion chamber promotes more thorough combustion and allows the ignition timing to be retarded, decreasing the dwell time of hot gases in the combustion chamber and reducing NO<sub>x</sub> formation. Many engine designs induce turbulence into the combustion chamber by increasing the velocity of the incoming air-fuel mixture and having it enter the chamber in a swirling motion (known as “swirl”).

### *Improved EGR Design*

One of the most effective means of reducing engine-out NO<sub>x</sub> emissions is exhaust gas recirculation. By recirculating spent exhaust gases into the combustion chamber, the overall air-fuel mixture is diluted, lowering peak combustion temperatures and reducing NO<sub>x</sub>. As discussed above, the use of high swirl, high turbulence combustion chambers can allow the amount of EGR to be increased from current levels of 15 to 17 percent to levels possibly as high

as 20 to 25<sup>a</sup> percent, resulting in a 15 to 20 percent reduction in engine-out NOx emissions.

Many EGR systems in today's vehicles utilize a control valve that requires vacuum from the intake manifold to regulate EGR flow. Under part-throttle operation where EGR is needed, engine vacuum is sufficient to open the valve. However, during throttle applications near or at wide-open throttle, engine vacuum is too low to open the EGR valve. While EGR operation only during part-throttle driving conditions has been sufficient to control NOx emissions for most vehicles in the past, more stringent NOx standards and emphasis on controlling off-cycle emission levels may require more precise EGR control and additional EGR during heavy throttle operation to reduce NOx emissions. Many manufacturers now use electronic EGR in place of mechanical back-pressure designs. By using electronic solenoids to open and close the EGR valve, the flow of EGR can be more precisely controlled.

While most manufacturers agree that electronic EGR gives more precise control of EGR flow rate, not all manufacturers are using it. Numerous LEV vehicles certified for the 1998 model year still use mechanical EGR systems, and in some cases, no EGR at all. Nonetheless, the use of EGR remains a very important tool in reducing engine-out NOx emissions, whether mechanical or electronic.

### *Multiple Valves and Variable-Valve Timing*

Conventional engines have two valves per cylinder, one for intake of the air-fuel mixture and the other for exhaust of the combustion products. The duration and lift (distance the valve head is pushed away from its seat) of valve openings is constant regardless of engine speed. As engine speed increases, the aerodynamic resistance to pumping air in and out of the cylinder for intake and exhaust also increases. By doubling the number of intake and exhaust valves, pumping losses are reduced, improving the volumetric efficiency and useful power output.

In addition to gains in breathing, the multiple-valve (typically 4-valve) design allows the spark plug to be positioned closer to the center of the combustion chamber (as discussed above) which decreases the distance the flame must travel inside the chamber. In addition, the two streams of incoming gas can be used to achieve greater mixing of air and fuel, further increasing combustion efficiency which lowers engine-out HC emissions.

Even greater improvements to combustion efficiency can be realized by using valve timing and lift control to take advantage of the 4-valve configuration. Conventional engines utilize fixed-valve timing and lift across all engine speeds. Typically the valve timing is set at a level that is a compromise between low speed torque and high engine speed horsepower. At light

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<sup>a</sup> Some manufacturers have stated that EGR impacts the ability to control net air-fuel ratios tightly due to dynamic changes in exhaust back pressure and temperature, and that the advantages of increasing EGR flow rates are lost partly in losses in air-fuel ratio control even with electronic control of EGR. Higher EGR flow rates can be tolerated by modern engines with more advanced combustion chambers, but EGR cooling may be necessary to achieve higher EGR flow rates within acceptable detonation limits without significant loss of air-fuel control.

engine loads it would be desirable to close the intake valve earlier to reduce pumping losses. Variable valve timing can enhance both low speed torque and high speed horsepower with no necessary compromise between the two. Variable valve timing can allow for increased swirl and intake charge velocity, especially during low load operating conditions where sufficient swirl and turbulence tend to be lacking. By providing a strong swirl formation in the combustion chamber, the air-fuel mixture can mix sufficiently, resulting in a faster, more complete combustion, even under lean air-fuel conditions, thereby reducing emissions. Variable valve technology by itself may have somewhat limited effect on reducing emissions. Several vehicle manufacturers estimated emission reductions of 3 percent-10 percent for both NMHC and NO<sub>x</sub>, but reductions could be increased when variable valve timing is combined with optimized spark plug location and additional EGR.

Multi-valve engines already exist in numerous federal and California certified vehicles and are projected by ARB to become even more common. ARB also projects that in order to meet LEV II and ULEV II standards, more vehicles will have to make improvements to the induction system, including the use of variable valve timing.

### *Leak-Free Exhaust System*

Leaks in the exhaust system can result in increased emissions, but not necessarily from emissions escaping from the exhaust leak to the atmosphere. With an exhaust system leak, ambient air is typically sucked into the exhaust system by the pressure difference created by the flowing exhaust gases inside the exhaust pipe. The air that is sucked into the exhaust system is unmetered and, therefore, unaccounted for in the fuel system's closed-loop feedback control. The excess air in the exhaust causes the computer to increase fuel to the engine, resulting in erratic and/or overly rich fuel control. This results in increased emission levels and potentially poor driveability. In addition, an air leak can cause an oxidation environment to exist in a three-way catalyst at low speeds that would hamper reduction of NO<sub>x</sub> and lead to increased NO<sub>x</sub> emissions.

Some vehicles currently use leak-free exhaust systems today. These systems consist of an improved exhaust manifold/exhaust pipe interface plus a corrosion-free flexible coupling inserted between the exhaust manifold flange and the catalyst to reduce stress and the tendency for leakage to occur at the joint. In addition, improvements to the welding process for catalytic converter canning could ensure less air leakage into the converter and further reduce emissions. ARB and MECA project that vehicle manufacturers will continue to incorporate leak-free exhaust systems as emission standards become more stringent.

### *ii. Improvements in Air-Fuel Ratio Control*

Modern three-way catalysts require the air-fuel ratio (A/F) to be as close to stoichiometry (the amount of air and fuel just sufficient for nearly complete combustion) as possible. This is because three-way catalysts simultaneously oxidize HC and CO, and reduce NO<sub>x</sub>. Since HC and

CO are oxidized during A/F operation slightly lean of stoichiometry, while NO<sub>x</sub> is reduced during operation slightly rich of stoichiometry, there exists a very small A/F window of operation around stoichiometry where catalyst conversion efficiency is maximized for all three pollutants (i.e., less than 1 percent deviation in A/F or roughly  $\pm 0.15$ ). Contemporary vehicles have been able to maintain stoichiometry, or very close to it, by using closed-loop feedback fuel control systems. At the heart of these systems has been a single heated exhaust gas oxygen (HEGO) sensor. The HEGO sensor continuously switches between rich and lean readings. By maintaining an equal number of rich readings with lean readings over a given period, and by limiting the degree to which the exhaust is rich or lean at any point in time, the fuel control system is able to maintain stoichiometry. While this fuel control system is capable of maintaining the A/F with the required accuracy under steady-state operating conditions, the system accuracy is challenged during transient operation where rapidly changing throttle conditions occur. Also, as the sensor ages, its accuracy decreases.

### *Dual Oxygen Sensors*

Many vehicle manufacturers have placed a second HEGO sensor(s) downstream of one or more catalysts in the exhaust system as a method for monitoring the catalyst effectiveness of the federally and California mandated on-board diagnostic (OBD II) system. In addition to monitoring the effectiveness of the catalyst, the downstream sensors can also be used to monitor the primary control sensor and adjust for deterioration, thereby maintaining precise A/F control at higher mileages. Should the front primary HEGO sensor, which operates in a higher temperature environment, begin to exhibit slow response or drift from its calibration point, the secondary downstream sensor can be relied upon for modifying the fuel system controls to compensate for the aging effects. By placing the second sensor further downstream from the hot engine exhaust, where it is also less susceptible to poisoning, the rear sensor is less susceptible to aging over the life of the vehicle. As a result, the use of a dual oxygen sensor fuel control system can ensure more robust and precise fuel control, resulting in lower emissions.

Currently, all vehicle manufacturers use a dual oxygen sensor system for monitoring the catalyst as part of the OBD II system. As discussed above, most manufacturers also utilize the secondary HEGO sensor for trim (i.e., adjustments to) of the fuel control system. It is anticipated that all manufacturers will soon use the secondary sensor for fuel trim.

### *Universal Oxygen Sensors*

The universal exhaust gas oxygen (UEGO) sensor, also called a "linear oxygen sensor", could replace conventional HEGO sensors. Conventional HEGO sensors only determine if an engine's A/F is richer or leaner than stoichiometric, providing no indication of the exact level of the A/F. In contrast, UEGO's are capable of recognizing both the direction and magnitude of A/F transients since the voltage output of the UEGO is "proportional" with changing A/F (i.e., each voltage value corresponds to a certain A/F). Therefore, proportional A/F control is possible with the use of UEGO sensors, facilitating faster response of the fuel feedback control system and tighter control of A/F.

Although some manufacturers are currently using UEGO sensors, discussions with various manufacturers suggest that some manufacturers are of mixed opinion as to the future applicability of UEGO sensors. Because of their high cost, manufacturers claim that it may be cheaper to improve HEGO technology rather than utilize UEGO sensors. An example of this is the use of a “planar” design for HEGO sensors. Planar HEGO sensors (also known as “fast light-off” HEGO sensors) have a thimble design that is considerably lighter than conventional designs. The main benefits are shorter heat-up time and faster sensor response.

### *Individual Cylinder A/F Control*

Another method for tightening fuel control is to control the A/F in each individual cylinder. Current fuel control systems control the A/F for the entire engine or a bank of cylinders. By controlling A/F for the entire engine or a bank of cylinders, any necessary adjustments made to fuel delivery for the engine are applied to all cylinders simultaneously, regardless of whether all cylinders need the adjustment. For example, there is usually some deviation in A/F between cylinders. If a particular cylinder is rich, but the "bulk" A/F indication for the engine is lean, the fuel control system will simultaneously increase the amount of fuel delivered to all of the cylinders, including the rich cylinder. Thus, the rich cylinder becomes even richer having a potentially negative effect on the net A/F.

Individual cylinder A/F control helps diminish variation among individual cylinders. This is accomplished by modeling the behavior of the exhaust gases in the exhaust manifold and using sophisticated software algorithms to predict individual cylinder A/F. Individual cylinder A/F control requires use of an UEGO sensor in lieu of the traditional HEGO sensor, and requires a more powerful engine control computer.

### *Adaptive Fuel Control Systems*

The fuel control systems of virtually all current vehicles incorporate a feature known as "adaptive memory" or "adaptive block learn." Adaptive fuel control systems automatically adjust the amount of fuel delivered to compensate for component tolerances, component wear, varying environmental conditions, varying fuel compositions, etc., to more closely maintain proper fuel control under various operating conditions.

For most fuel control systems in use today, the adaption process affects only steady-state operation conditions (i.e., constant or slowly changing throttle conditions). Because transient operating conditions have always provided a challenge to maintaining precise fuel control, the use of adaptive fuel control for transient operation would be extremely valuable. Accurate fuel control during transient driving conditions has traditionally been difficult because of inaccuracies in predicting the air and fuel flow under rapidly changing throttle conditions. Air and fuel dynamics within the intake manifold (fuel evaporation and air flow behavior), and the time delay between measurement of air flow and the injection of the calculated fuel mass, result in temporarily lean A/F during transient operation. Variation in fuel properties, particularly

distillation characteristics, also increases the difficulty in predicting A/F during transients. These can all lead to poor driveability and an increase in NO<sub>x</sub> emissions.

### *Electronic Throttle Control Systems*

As mentioned above, the time delay between the air mass measurement and the calculated fuel delivery presents one of the primary difficulties in maintaining accurate fuel control and good driveability during transient driving conditions. With the conventional mechanical throttle system (a metal linkage connected from the accelerator pedal to the throttle blade in the throttle body), quick throttle openings can result in a lean A/F spike in the combustion chamber. Although algorithms can be developed to model air and fuel flow dynamics to compensate for these time delay effects, the use of an electronic throttle control system, known as “drive-by-wire” or “throttle-by-wire,” may better synchronize the air and fuel flow to achieve proper fueling during transients (e.g., the driver moves the throttle, but the fuel delivery is momentarily delayed to match the inertial lag of the increased airflow).

While this technology is currently used on several vehicle models, it is considered expensive and those vehicles equipped with the feature are expensive, higher end vehicles. Because of its high cost, it is not anticipated that drive-by-wire technology will become commonplace in the near future.

### *iii. Improvements in Fuel Atomization*

In addition to maintaining a stoichiometric A/F ratio, it is also important that a homogeneous air-fuel mixture be delivered at the proper time and that the mixture is finely atomized to provide the best combustion characteristics and lowest emissions. Poorly prepared air-fuel mixtures, especially after a cold start and during the warm-up phase of the engine, result in significantly higher emissions of unburned HC since combustion of the mixture is less complete. By providing better fuel atomization, more efficient combustion can be attained, which should aid in improving fuel economy and reducing emissions. Sequential multi-point fuel injection and air-assisted fuel injectors are examples of the most promising technologies available for improving fuel atomization.

### *Sequential Multi-Point*

Typically, conventional multi-point fuel injection systems inject fuel into the intake manifold by injector pairs. This means that rather than injecting fuel into each individual cylinder, a pair of injectors (or even a whole bank of injectors) fires simultaneously, sending fuel into several cylinders. Since only one of the cylinders is actually ready for fuel at the moment of injection, the other cylinder(s) gets too much or too little fuel. With this less than optimum fuel injection timing, fuel puddling and intake manifold wall wetting can occur, both of which can hinder complete combustion. Sequential injection, on the other hand, delivers a more precise amount of fuel that is required by each cylinder to each cylinder at the appropriate time. Because of the emission reductions and other performance benefits “timed” fuel injection offers,



sequential fuel injection systems are very common on today's vehicles and are expected to be incorporated in all vehicles soon.

### *Air-Assisted Fuel Injectors*

Another method to further homogenize the air-fuel mixture is through the use of air-assisted fuel injection. By injecting high pressure air into the fuel injector, and subsequently, the fuel spray, greater atomization of the fuel droplets can occur. Since achieving good fuel atomization is difficult when the air flow into the engine is low, air-assisted fuel injection can be particularly beneficial in reducing emissions at low engine speeds. In addition, industry studies have shown that the short burst of additional fuel needed for responsive, smooth transient maneuvers can be reduced significantly with air-assisted fuel injection due to a decrease in wall wetting in the intake manifold.

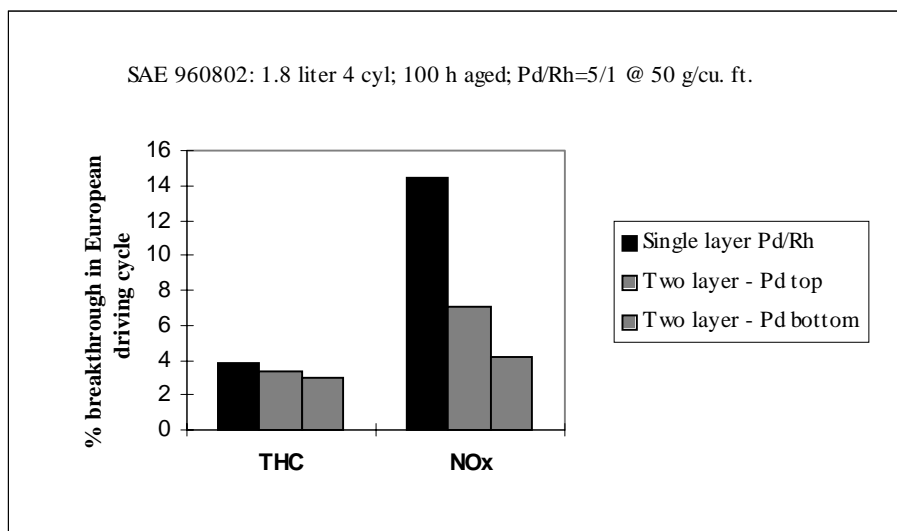
### *iv. Improvements to Exhaust Aftertreatment Systems*

Over the last five years or so, there have been tremendous advancements in exhaust aftertreatment systems. Catalyst manufacturers are progressively moving to palladium as the main precious metal in automotive catalyst applications. Improvements to catalyst thermal stability and washcoat technologies, the design of higher cell densities, and the use of two-layer washcoat applications are just some of the advancements made to catalyst technology. There has also been much development in HC and NO<sub>x</sub> absorber technology. The advancements to exhaust aftertreatment systems are probably the single most important area of emission control development.

### *Catalysts*

As previously mentioned, significant changes in catalyst formulation, size and design have been made in recent years and additional advances in these areas are still possible. Palladium (Pd) is likely to continue as the precious metal of choice for close-coupled applications and will start to see more use in underfloor applications. Some manufacturers, for example, have suggested that they will use Pd/Rh in lieu of tri-metal or conventional Pt/Rh catalysts for underfloor applications. Palladium catalysts, however, are less resistant to poisoning by oil-and fuel-based additives than conventional platinum/rhodium (Pt/Rh) catalysts. Based on current certification trends and information from vehicle manufacturers and catalyst suppliers, it is expected that Pd-only and Pd/Rh catalysts will be used in the close-coupled locations while conventional or tri-metal (Pd/Pt/Rh) catalysts will continue to be used in underfloor applications. As palladium technology continues to improve, it may be possible for a single close-coupled catalyst to replace both catalysts. In fact, at least one vehicle manufacturer currently uses a single Pd-only catalyst for one of their models. According to MECA, new Pd-based catalysts are now capable of withstanding exposure to temperatures as high as 1100°C and, as a result, can be moved very close to the exhaust manifold to enhance catalyst light-off performance.

In addition to reliance on Pd and tri-metal applications, catalyst manufacturers have developed “multi-layered” washcoat technologies. Automotive catalysts consist of a cylindrical or oval shaped substrate, typically made of ceramic or metal. The substrate is made up of hundreds of very small, but long cells configured in a shape similar to a honey-comb. The substrate is coated with a substance containing precious metals, rare earth metals, and base-metal oxides, that is known as the catalyst washcoat. Typical washcoat formulations consist of precious metals which either oxidize or reduce pollutants, base-metal oxides, such as alumina, which provide the surface area support for the precious metals to adhere to, and base components (rare earth metals) such as lanthanum, ceria, and zirconia, which act as promoters, stabilizers, and encourage storage and reduction of oxygen. Conventional catalysts have a single layer of washcoat and precious metals applied to the catalyst substrate. More advanced catalysts use multi-layered washcoats with two or more layers of different combinations of washcoat and precious metals. The washcoat can be applied to the substrate such that one layer can be applied on top of another. The use of multi-layered washcoat technology allows precious metals that have adverse reactions together to be separated such that catalyst durability and emission reduction performance are significantly enhanced. For example, Pd and Rh can have adverse reactions when combined together in a single washcoat formulation. A multi-layer washcoat architecture that uses Pd and Rh could have the Pd on the bottom layer and the Rh on the top layer. Rh is particularly used at reducing NO<sub>x</sub>. It is generally preferable to reduce NO<sub>x</sub> in the top layer while CO and HC are still present and then oxidize CO and HC in the bottom layer. Figure IV-1 illustrates the impact coating architecture (multi-layered washcoat technology) can have on emission performance.



**Figure IV-1. Impact of Coating Architecture on HC and NO<sub>x</sub> Emissions.**

Manufacturers have also been developing catalysts with substrates which utilize thinner walls in order to design higher cell density, low thermal mass catalysts for close-coupled applications (improves mass transfer at high engine loads and increases catalyst surface area as well as speeding up light-off during cold starts). The greater the number of cells there are, the

more surface area that exists for washcoat components and precious metals to adhere to, resulting in more precious metal sites available for oxidizing and reducing pollutants. Cell densities of 600 cells per square inch (cpsi) have already been commercialized, and research on 900 cpsi catalysts has been progressing. Typical cell densities for conventional catalysts are 400 cpsi.

We have projected that in order to meet the proposed Tier 2 emission standards catalyst volumes will increase. Current California LEV and ULEV passenger car catalyst volume to engine displacement ratios are approximately 0.7 to over 1.0 while many trucks only have ratios of 0.6 or less. We believe that in order to comply with proposed Tier 2 standards, most vehicle will likely need catalyst volumes equal to the displacement of the engine, or in some cases, even greater. As mentioned above, higher cell density substrates effectively provide more surface area for pollutant conversion, therefore catalyst volumes may not need to be increased as significantly if higher cell density substrates are used.

We have also projected that some level of increased catalyst loading will be necessary to meet proposed Tier 2 standards. Typical catalyst loading for current LEVs and ULEVs range from 50 g/cu ft to 300 g/cu ft. We believe that, based on input from catalyst suppliers and vehicle manufacturers, depending on the vehicle, catalysts meeting Tier 2 standards will need loadings in the 100 - 300 g/cu ft range. However, catalyst suppliers have also indicated to us that they and vehicle manufacturers are constantly working on ways to reduce the amount of precious metal loading ( a process they refer to as “thrifting”). Thrifting is achieved in several ways. One of the most common is matching the catalyst to the attributes of the vehicle. By working in unison, vehicle manufacturers and catalyst suppliers are able to thrift or reduce the amount of precious metal used in a given application by attempting to optimize the vehicle fuel control strategy, exhaust mass flow rate, and exhaust temperature with various catalyst parameters, such as catalyst location, substrate design, cell density, oxygen storage capability, and precious metal and base metal dispersion, to name a few. Other methods of thrifting are the constant improvements being made to washcoat architecture - that is, constant improvement to the materials used in the washcoat formulation so that the precious metals and other components better adhere to the substrate surface. Finally, improvements to washcoat application processes can also significantly improve catalyst performance while allowing thrifting of precious metals. Improvements to processes consist of advancements to the process used to coat the substrate with washcoat materials - allowing precious metals, base metals, and ceria to better dispersed. Better dispersion means that rather than relatively large “clumps” of precious metals unevenly dispersed throughout the catalyst surface, many smaller precious metal sites are dispersed uniformly throughout the catalyst surface increasing the chance for pollutants to come into contact with the precious metal and react into a harmless emission. Therefore, as thrifting continues, it is possible that precious metal loading may actually decrease rather than increase.

The largest source of HC emissions continues to be cold start operation where the combination of rich A/F operation and the ineffectiveness of a still relatively cool catalyst result in excess HC emissions. One of the most effective strategies for controlling cold start HC emissions is to reduce the time it takes to increase the operating temperature of the catalyst immediately following engine start-up. The effectiveness or efficiency of the catalyst increases

as the catalyst temperature increases. One common strategy is to move the catalyst closer to the exhaust manifold where the exhaust temperature is greater (e.g., a close-coupled catalyst). In addition to locating the catalyst closer to the engine, retarding the spark timing and increasing idle speed are other possible approaches. Retarding spark timing, causes combustion to occur later in the power stroke, allowing more heat to escape into the exhaust manifold during the exhaust stroke. Increased idle speed leads to a greater amount of combustion per unit time, providing a greater quantity of heat for heating the exhaust manifold, headpipe, and catalyst.

Another strategy is to use an electrically-heated catalyst (EHC). The EHC consists of a small electrically heated catalyst placed directly in front of a conventional catalyst. Both substrates are located in a single can or container. The EHC is powered by the alternator, or solely from the vehicle's battery, or from a combination of the alternator and battery. The EHC is capable of heating up almost immediately, assisting the catalyst that directly follows it to also heat up and obtain light-off temperature (e.g., the catalyst temperature where catalyst efficiency is 50 percent) quickly. Manufacturers have indicated that EHC's will probably only be necessary for a limited number of LEV II/ULEV II engine families, mostly larger displacement V-8's where cold start emissions are difficult to control.

### *Adsorbers/Traps*

Other potential exhaust aftertreatment systems that are used in conjunction with a catalyst or catalysts, are the HC and NO<sub>x</sub> adsorbers or traps. Hydrocarbon adsorbers are designed to trap HC while the catalyst is cold and unable to sufficiently convert the HC. They accomplish this by utilizing an adsorbing material which holds onto the HC. Once the catalyst is warmed up, the trapped HC are automatically released from the adsorption material and are converted by the fully functioning downstream three-way catalyst. There are three principal methods for incorporating an adsorber into the exhaust system. The first is to coat the adsorber directly on the catalyst substrate. The advantage is that there are no changes to the exhaust system required, but the desorption process cannot be easily controlled and usually occurs before the catalyst has reached light-off temperature. The second method locates the adsorber in another exhaust pipe parallel with the main exhaust pipe, but in front of the catalyst and includes a series of valves that route the exhaust through the adsorber in the first few seconds after cold start, switching exhaust flow through the catalyst thereafter. Under this system, mechanisms to purge the adsorber are also required. The third method places the trap at the end of the exhaust system, in another exhaust pipe parallel to the muffler, because of the low thermal tolerance of adsorber material. Again a purging mechanism is required to purge the adsorbed HC back into the catalyst, but adsorber overheating is avoided.

NO<sub>x</sub> adsorbers are also being developed, but according to MECA, are generally recognized as a control for NO<sub>x</sub> resulting from reduced EGR. They are typically used for lean-burn applications and are not applicable to engines that attempt to maintain stoichiometry all the time.

### *Secondary Air Injection*

Secondary injection of air into exhaust ports after cold start (e.g., the first 40-60 seconds) when the engine is operating rich, coupled with spark retard, can promote combustion of unburned HC and CO in the exhaust manifold and increase the warm-up rate of the catalyst. By means of an electrical pump, secondary air is injected into the exhaust system, preferably in close proximity of the exhaust valve. Together with the oxygen of the secondary air and the hot exhaust components of HC and CO, oxidation ahead of the catalyst can bring about an efficient increase in the exhaust temperature which helps the catalyst to heat up quicker. The exothermic reaction that occurs is dependent on several parameters (secondary air mass, location of secondary air injection, engine A/F ratio, engine air mass, ignition timing, manifold and headpipe construction, etc.), and ensuring reproducibility demands detailed individual application for each vehicle or engine design.

### *Insulated or Dual Wall Exhaust System*

Insulating the exhaust system is another method of furnishing heat to the catalyst to decrease light-off time. Similar to close-coupled catalysts, the principle behind insulating the exhaust system is to conserve heat generated in the engine to aid the catalyst warm-up. Through the use of laminated thin-wall exhaust pipes, less heat will be lost in the exhaust system, enabling quicker catalyst light-off.

### *v. Improvements in Engine Calibration Techniques*

Of all the technologies discussed above, one of the most important emission control strategies is not hardware-related. Rather, it is software related and, more specifically, involves the algorithms and calibrations contained within the software that are used in the power-train control module (PCM) which control how the various engine and emission control components and systems operate. Advancements in software along with refinements to existing algorithms and calibrations can have a major impact in reducing emissions. Confidential discussions between manufacturers and EPA have suggested that manufacturers believe emissions can be further reduced by improving and updating their calibration techniques. As computer technology and software continues to advance, so does the ability of the automotive engineer to use these advancements in ways to better optimize the emission control systems. For example, as processors become faster, it is possible to perform calculations quicker, thus allowing for faster response times for controlling engine parameters, such as fuel rate and spark timing. As the PCM becomes more powerful with greater memory capability, algorithms can become more sophisticated. Manufacturers have found that as computer processors, engine control sensors and actuators, and computer software become more advanced, and, in conjunction with their growing experience with developing calibrations, as time passes, their calibration skills will continue to become more refined and robust, resulting in even lower emissions.

Manufacturers have suggested to EPA that perhaps the single most effective method for controlling NO<sub>x</sub> emissions will be tighter A/F control which could be accomplished with advancements in calibration techniques without necessarily having to use advanced technologies,

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such as UEGO sensors. Manufacturers have found ways to improve calibration strategies such that meeting federal cold CO requirements, as well as, complying with LEV standards, have not required the use of advanced hardware, such as EHCs or adsorbers.

Since emission control calibrations are typically confidential, it is difficult to predict what advancements will occur in the future, but it is clear that improved calibration techniques and strategies are a very important and viable method for further reducing emissions.

### **b. Data Supporting Tier 2 Technical Feasibility**

Automobile manufacturers generally design vehicles to meet emission targets which are 50-70 percent of the emission standards, even after the catalytic converter has been aged to full useful life (e.g., 100,000-120,000 miles). The manufacturer desires this 30-50 percent safety margin in order to reduce the probability that in-use vehicles will exceed the standard to an acceptable level. Thus, the emission design targets for proposed Tier 2 standards for full useful life would be 0.045-0.063 g/mi NMOG and 0.035-0.049 g/mi NO<sub>x</sub> at full useful life.

With this in mind, we will present data from several sources that establish our proposed Tier 2 standards to be feasible. The data ranges from certification emission levels to feasibility evaluation programs undertaken in the last year by ARB and MECA. Even though these programs were directed towards the LEV II program, the data and information resulting from these programs are useful to EPA in establishing feasibility of Tier 2 emission standards since our proposed Tier 2 standards are the same as the LEV II standards.

#### *i. Certification Emission Levels*

Manufacturers report certification results for engine families. Those engine families are used in a variety of vehicle models and configurations. Manufacturers are required to report certification test results for at least two vehicle configurations and often report results for five or six or more models or configurations within an engine family. Manufacturers, for example, will report certification test results for both automatic and manual transmission versions of a vehicle. Table IV-2 below indicates the number of engine families with at least one vehicle configuration at or below full-life NO<sub>x</sub> levels of 0.04, 0.07, and 0.1 g/mile. Of those at or below 0.04 and 0.07 g/mile NO<sub>x</sub>, 16 and 35, respectively, also have HC levels below 0.09 g/mile. There are approximately 400 engine families total.

**Table IV-2. Number of Engine Families with One or More Engine/Vehicle Configurations with Low Full-life NOx Levels**

<i>NOx level</i>	<i>Vehicles Below 6,000 pounds (LDVs, LDT1s, LDT2s)</i>	<i>Vehicles Above 6,000 pounds (LDT3s, LDT4s)</i>
$\leq 0.04$	20	2
$\leq 0.07$	45	3
$\leq 0.1$	150	11

Table IV-3 provides a listing of engine families with one or more vehicle configurations at or below 0.07 g/mile NOx. The table also provides the HC certification levels for those configurations. Where a range is shown, there is more than one configuration within the engine family with full-life NOx certification levels at or below 0.07. The same vehicle models appear in the table more than once because multiple engine families are often certified for the same vehicle models. EPA assembled this list by reviewing 1999 model year certification data for engine families certified to nationwide Tier 1 standards, NLEV program standards, and the California program standards.

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**Table IV-3. 1999 Engine Families with One or More Vehicle Configurations with Full-life NOx Certification Levels at or below 0.07 g/mile NOx**

<i>Manufacturer</i>	<i>Models</i>	<i>NOx level</i>	<i>HC level</i>	<i>Standard</i>
LDVs (passenger cars)				
Hyundai	Elantra Wagon, Tiburon	0.01 - 0.02	0.05	LEV
Ford	Contour, Mystique, Cougar	0.02 - 0.05	0.12 - 0.17	Tier 1
Ford	Contour, Mystique, Cougar	0.02*	0.12	Tier 1
Volkswagon, Audi	Passat, Passat wagon A4	0.03 - 0.07*	0.06 - 0.07	TLEV
Volvo	V70, S70	0.03	0.06 - 0.08	TLEV
Volvo	S70, V70, C70	0.03 - 0.04	0.05 - 0.07	LEV
Hyundai	Elantra, Tiburon	0.03 - 0.04**	0.04 - 0.06	Tier 1
Daimler Chrysler	Cirrus, Stratus, Breeze	0.04**	0.06	LEV
Mitsubishi	Diamante	0.04**	0.05	LEV
Mitsubishi	Gallant, Mirage	0.04 +	0.03	LEV
Suzuki	Metro	0.04	0.03	TLEV
Ford	Mustang	0.04	0.17 - 0.21	Tier 1
Ford	Contour, Mystique, Cougar	0.04 - 0.05	0.07 - 0.08	TLEV
Daimler Chrysler	S320	0.04 +	0.07	Tier 1
Hyundai	Sonata	0.04 - 0.06*	0.07	TLEV
Volkswagon	Jetta, Golf, Cabriolet	0.04 - 0.06	0.04 - 0.07	TLEV
Nissan	Altima	0.05	0.03	LEV
Ford	Sable, Taurus	0.05 - 0.06	0.13 - 0.14	Tier 1
Ford	Mustang	0.05 - 0.06	0.07	TLEV
Ford	Contour, Mystique, Cougar	0.06	0.07	Tier 1
Daimler Chrysler	E430, SL500	0.06 - 0.07	0.02	LEV
Daimler Chrysler	SL600	0.06	0.12	Tier 1
Hyundai	Accent	0.06*	0.08 - 0.1	TLEV
Hyundai	Sonata	0.06*	0.04 - 0.05	TLEV
Volkswagon	New Beetle, New Golf, New Jetta	0.06*	0.06	LEV
Mazda	MX-5 Miata	0.07	0.07	TLEV



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Mitsubishi	Mirage	0.07	0.05	LEV
Volvo	S80	0.06 - 0.07*	0.07 - 0.08	TLEV
Volvo	S80	0.04 - 0.05	0.11	TLEV
Daimler Chrysler	C230 Kompressor	0.07	0.03	TLEV
Honda	Accord	0.07*	0.04 - 0.05	LEV
Honda	Civic HX	0.07*	0.09	TLEV
Honda	Civic	0.07*	0.07 - 0.08	TLEV
Infiniti	Q45	0.07*	0.11	Tier 1
LDT 1				
Daimler Chrysler	Jeep Cherokee 2WD, 4WD	0.03* <sup>+</sup>	0.06	Tier 1
Ford	Ranger	0.04 - 0.07	0.09 - 0.18	Tier 1
Mazda	B2500, B3000	0.04 - 0.06	0.08 - 0.13	Tier 1
Ford	Ranger	0.05*	0.11	Tier 1
LDT2				
Ford	Explorer	0.03 - 0.04	0.07 - 0.10	Tier1
Ford, Mazda	Ranger, B3000	0.04 - 0.07	0.12 - 0.15	Tier 1
Ford	F-150	0.05*	0.08 - 0.10	Tier 1
Mazda	B3000	0.05*	0.06 - 0.07	Tier 1
Ford, Mazda	Ranger, B3000	0.05 - 0.07	0.07 - 0.12	Tier 1
Daimler Chrysler	Caravan, Voyager	0.07		LEV
Nissan	Frontier	0.07*	0.07	LEV
LDT3				
Ford	F-150	0.04 - 0.06	0.07 - 0.08	Tier 1
Ford	F-150	0.05 - 0.06	0.11 - 0.12	Tier 1
LDT4				
Ford	Expedition, Navigator, F-250	0.04*	0.16 - 0.17	Tier 1

\* Other model configurations have NO<sub>x</sub> certification levels above 0.07 g/mile

+ The official NO<sub>x</sub> certification result reported was 0 for these vehicles due to rounding. The values shown are the unrounded results.

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A review of the Table above shows that most of the engine families with configurations certified at 0.07 g/mile NO<sub>x</sub> or less are passenger cars and lighter weight LDTs . This is understandable since all LDT classes except LDT1 have emission standards considerably higher than LDVs. Thus, to this point, there has been no motivation for vehicle manufacturers to design and produce light-duty trucks with emission control systems on par with light-duty vehicle systems. Even so, there are several light-duty trucks with certification levels at or very close to the proposed Tier 2 requirements.

### *ii. Industry Sulfur Test Program*

The Coordinating Research Council (CRC), automobile manufacturers and the American Petroleum Institute (API) all tested a number of vehicles capable of complying with the California LEV or ULEV standards. The primary purpose of these test programs was to estimate how higher fuel sulfur levels affected emissions. However, the test results with low sulfur fuel (i.e., 30-40 ppm sulfur) provide an indication of the emission control potential of these vehicles. Of the 20 unique vehicle models tested in these programs, four models met both of the Tier 2 NMOG and NO<sub>x</sub> design targets mentioned above. An additional three models had NMOG levels below the design targets and NO<sub>x</sub> levels above the design targets, but below the proposed NO<sub>x</sub> standard. All of these low emitting models were LDVs with 100K catalyst systems.

### *iii. MECA Test Program*

The Manufacturers of Emission Controls Association (MECA) sponsored vehicle emission testing at the Southwest Research Institute (SwRI)<sup>1</sup> for the purpose of demonstrating the performance of advanced emission control systems in meeting proposed California LEV II and our proposed Tier 2 light-duty vehicle standards. SwRI took two LDVs (a 1997 3.8L Buick LeSabre and a 1997 4.6L Ford Crown Vic) and one LDT2 (3.4L Toyota T100) certified to the federal Tier 1 standards and replaced the original catalytic converters with more advanced catalytic converters provided by MECA members. The catalysts were thermally aged to roughly 50,000 mile of in-use operation. SwRI then attempted to optimize the emission performance by modifying the existing secondary air and exhaust gas recirculation (EGR) strategies. This was accomplished by using a computer controlled intercept system (Emissions Reduction Intercept and Control system or ERIC). This computer intercept methodology was used to recognize and modify only driving modes associated with high tailpipe emission modes, thereby minimizing the level of modifications to the base vehicle control system. The control tuning approach developed for each vehicle was unique to the individual vehicle. The computer intercept techniques used in this program were capable of modifying secondary air and EGR without setting any on-board diagnostic codes. The modified control strategies also did not have any measurable impact on fuel economy, nor were any detectable changes to vehicle driveability observed during FTP evaluations.

After these modifications, all three vehicles met the Tier 2 NMOG usefull life design

targets. The LeSabre and T100 both met the NO<sub>x</sub> design target. The Crown Victoria, however was a little short of the design target, but did meet the proposed Tier 2 standard with a headroom of 23 percent. The actual test results are summarized in Table IV-4 below.

**Table IV-4. MECA Test Program: Emissions with Catalysts Aged to 100,000 Miles (g/mi).**

	<i>NMOG</i>	<i>NO<sub>x</sub></i>
Tier 2 Design Targets	0.045-0.063	0.035-0.049
Crown Victoria (LDV)	0.049	0.057
Buick LeSabre (LDV)	0.038	0.037
Toyota T100 (LDT2)	0.052	0.014

*iv. ARB Test Program*

ARB tested five different 1997-98 model year production LEV LDV models. Two of the six models met the proposed Tier 2 design targets for NMOG and NO<sub>x</sub>. Each vehicle was tested for baseline emissions at approximately 1K miles before any modifications to the vehicle's emission controls were made. Table IV-5 lists the average emissions from these FTP tests.

**Table IV-5. ARB Production LEV LDV Passenger Car Emission Data.**

<i>Test Vehicle</i>	<i>NMHC (g/mi)</i>	<i>CO (g/mi)</i>	<i>NO<sub>x</sub> (g/mi)</i>
1997 Mercury Sable	0.035	0.9	0.072
1998 Mercury Grand Marquis	0.048	0.6	0.014
1998 Nissan Altima	0.031	0.7	0.040
1998 Honda Accord EX	0.025	0.3	0.066
1998 Toyota Avalon	0.044	0.4	0.111

After the baseline FTP results were complete, new advanced catalysts supplied by various catalyst suppliers were installed on each test vehicle. In general, the advanced catalysts were placed in the same position as the OEM catalysts. Two of the vehicles had small close-coupled catalysts added to the OEM configuration. FTP tests were then conducted. If the emission results were not below the proposed LEV II standards with a reasonable margin, engine calibration modifications such as spark retard at engine start, O<sub>2</sub> sensor biasing (typically rich), or secondary air injection modifications were made to reduce tailpipe emission levels further. In a couple of instances, approximately 4K miles were accumulated on the "green" catalysts before

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FTP tests were conducted again. All of the vehicles, once modified, had emission levels well below the proposed Tier 2 NMOG and NO<sub>x</sub> design targets. While these results are not with catalysts aged to full useful life, we believe these results are still very promising, since in-use deterioration rates have been steadily declining. Even if these emissions were to double, they would still be very close to or below the proposed Tier 2 standards. Table IV-6 lists the modified passenger car emission results.

**Table IV-6. ARB Modified Passenger Car Emission Data  
(advanced catalysts with modifications to fuel and/or spark & secondary air)**

<i>Manufacturer</i>	<i>Model</i>	<i>Mileage</i>	<i>NMOG (g/mi)</i>	<i>CO (g/mi)</i>	<i>NO<sub>x</sub> (g/mi)</i>
Mercury	Sable	0	0.029	1.0	0.036
Mercury	Grand Marquis	4000	0.033	0.5	0.004
Nissan	Altima	0	0.028	0.7	0.033
Honda	Accord EX	0	0.026	0.4	0.035

ARB also tested two identical 1998 Ford Expeditions (LDT4). Both vehicles were tested in the baseline OEM configuration at 2,000 miles with promising results. Table IV-7 lists the baseline emission results for the two Expeditions.

**Table IV-7. ARB Ford Expedition Baseline Emission Test Results**

<i>Vehicle</i>	<i>No. of Tests</i>	<i>NMHC (g/mi)</i>	<i>CO (g/mi)</i>	<i>NO<sub>x</sub> (g/mi)</i>
#2	8	0.090	1.69	0.030
#3	6	0.077	1.57	0.031

ARB installed advanced Pd/Rh catalyst systems bench aged to 50,000 miles along with 50,000 mile bench aged oxygen sensors on both vehicles and were able to reduce NO<sub>x</sub> emissions about 50 percent from the NO<sub>x</sub> certification level of 0.14 g/mi. ARB also added secondary air to the vehicles and made some modifications to the spark timing (retarded) and oxygen sensor bias (rich) and found that they were able to further reduce emissions. Table IV-8 lists the emission results of the Expeditions with advanced catalyst systems.

**Table IV-8. ARB Expedition Emission Results with Advanced Catalyst Systems**

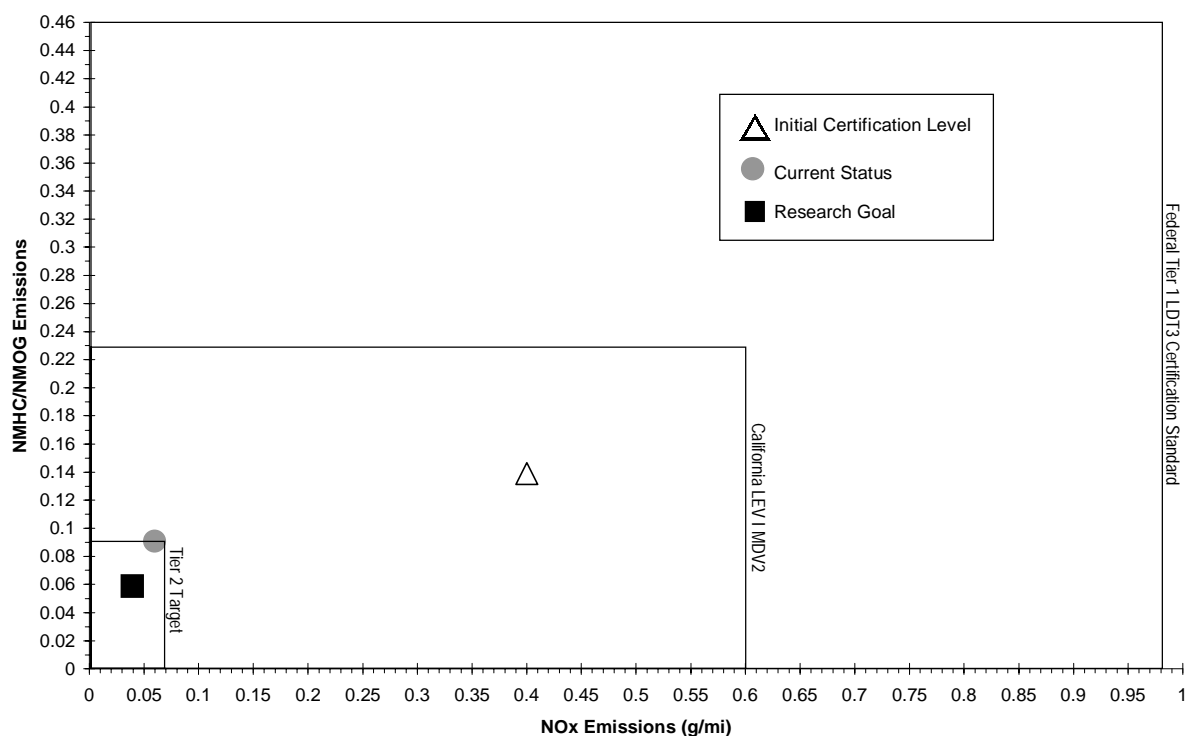
<i>Vehicle</i>	<i>No. Of Tests</i>	<i>NMHC (g/mi)</i>	<i>CO (g/mi)</i>	<i>NOx (g/mi)</i>
#2	4	0.111	3.32	0.048
#3	7	0.112	2.91	0.052

- *EPA Test Program*

Our test program was aimed at lowering the emissions of a large 1999 LDT3 vehicle. This vehicle has a high horsepower engine, four wheel drive, and a curb weight of 4,500 pounds (GVW of 6,000 lbs). The exhaust system of the pickup was modified to incorporate two close coupled and two underfloor catalytic converters provided by MECA. The catalytic converters used for these tests were nearly identical to the system used on “Vehicle 1” in the work by Webb et al.<sup>b</sup> The only modifications from the specification used by Webb et al. were insulation of the close coupled catalytic converters using a woven ceramic fiber mesh, and the use of a somewhat larger exhaust pipe diameter (same as OEM) to limit exhaust backpressure. All of the catalyst “bricks” were constructed of a 4-mil ceramic monolithic material. The two close coupled catalytic converters each used two “bricks” and were mounted immediately downstream of each exhaust manifold. The first “brick” in each close coupled catalytic converter had a diameter of 7.6 cm, was 7.6 cm long, with a cell density of 600 cpsi, and was coated with 250 g/ft<sup>3</sup> of Pd. The second “brick” in each close coupled catalytic converter had a diameter of 10.2 cm, was 8.5 cm long, with a cell density of 400 cpsi, and was coated with Pd/Rh at a 9:1 ratio to 150 g/ft<sup>3</sup>. The two underfloor catalytic converters each contained a single “brick” with a diameter of 10.2 cm, was 11.1 cm long, with a cell density of 400 cpsi, and was coated with Pd/Rh at a 9:1 to 80 g/ft<sup>3</sup>.

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<sup>b</sup>C.C Webb, B.B. Bykowski, P.A. Weber, D.L. McKinnon; “Using Advanced Emissions Control Systems to Demonstrate LEV II ULEV on Light-Duty Gasoline Vehicles”. SAE Technical Paper Series, Paper No. 1999-01-0774, 1999.



**Figure IV-2: Certification Emissions and Initial Research and Development Results for a Large 1999 LDT3 Pickup, as Compared to Federal Tier 1 Emissions Standards, California LEV-I Emissions Standards, and a Tier 2 Corporate Average Target.**

Initially, no attempts were made to alter the calibration of the electronic engine controls. Figure IV-2 shows emissions results from testing of the LDT3 vehicle. In this configuration, the pickup achieved emissions levels of  $0.060 \pm 0.002$  g/mi NOx and  $0.09 \pm 0.01$  g/mi NMHC. Based on initial modal emissions results, EPA staff engineers have indicated that the research targets of 0.04 g/mi NOx and 0.06 g/mi NMHC will likely be reached through elimination of fuel cut-offs during decelerations, slight increases in EGR, and a minor degree of air-injection during cold-start.

### v. *Summary of Technical Feasibility Data*

It is very apparent from the data presented above that it is technically feasible for LDVs to meet our proposed Tier 2 emission standards in the proposed time frame. Although the bulk of the data is for LDVs with smaller displacement engines, there are examples of vehicles with larger displacement engines - the 1999 Ford Mustang Convertible and the Ford Crown Vic and Buick LeSabre modified by MECA. Neither of the MECA or ARB test programs modified the basic engine calibrations of the vehicles tested. In general, the engine calibration is designed

specifically to match the engine exhaust to the catalytic converter being used on the vehicle. Since recalibrations optimize engine performance, durability, emissions and safety simultaneously, neither MECA nor ARB modified the original engine calibration. However, it is very likely that such recalibration could better match engine operation and the advanced catalytic converters being tested and reduce emissions beyond the emission levels measured in the test programs. Therefore, we are confident that by 2004, all LDVs should be capable of meeting Tier 2 standards.

Fewer data are available addressing the ability of LDTs to meet the design targets implied by the proposed Tier 2 NMOG and NO<sub>x</sub> standards. No current LDTs have been certified at such low emission levels. However, this is partially due to the fact that their current emission standards are generally well above those for LDVs. Also, the number of LDTs required to comply with ARB's current LEV and ULEV standards is much lower than the number of LDVs (and LDT1s). Thus, manufacturers have focused their early LEV and ULEV development efforts on LDVs.

The fact that a number of LDTs have been certified at emission levels near the proposed Tier 2 standards indicates that control technology has developed to the point where the differences between LDV and LDT emissions are shrinking.

As highlighted by MECA at the November 1998 annual meeting between EPA and MECA to discuss recent emission control technology developments, there are several areas where technology gaps exist between LDV and LDT technology. Table IV-9 lists these gaps.

**Table IV-9. Emission Technology Gaps Between LDVs and LDTs**

<i>LEV LDVs</i>	<i>Tier 1 LDTs</i>
Tight A/F control	Relatively loose A/F control
Close-coupled + underfloor catalyst combination	Underfloor catalyst with long pipe runs
Ratio of catalyst volume to engine displacement $V_{cat}/V_{eng} = 1-1.5$	$V_{cat}/V_{eng} = 0.5$ or less
Catalysts with advanced washcoats and higher cell density substrates	Less sophisticated catalysts on standard substrates

These differences have been due to the fact that LDT standards were less stringent than those applicable to LDVs. However, there are no technological reasons why LDTs cannot employ the exact same technology, or even better technology, as LDVs.

The Toyota T100 pick-up (LDT2) modified by MECA and optimized by SwRI had very impressive emission results at 50,000 miles - considerably lower than the Tier 2 design targets.

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The ARB Ford Expedition had emission reductions of over 50 percent from certification levels, achieving results just at the LEV II and Tier 2 NO<sub>x</sub> standard (NMOG was below the design target) with the addition of an advanced catalyst system and the introduction of secondary air at start-up. Finally, our own LDT3 test program had emission results below Tier 2 standards. As stated above, none of the above mentioned test programs modified the basic engine calibrations of the vehicles tested. The modifications they made were minor compared to what vehicle manufacturers are capable of doing. For example, the 1999 certification results for the Ford Expedition show a slight increase in NMOG levels relative to the 1998 model, but a 50 percent reduction in NO<sub>x</sub> levels at 50,000 miles. The full useful life NO<sub>x</sub> certification level in 1998 was 0.14 g/mi but only 0.07 g/mi in 1999. The only difference between the two model years is engine calibration - both model years have the same catalyst system. This highlights the importance of engine calibration on emission control system performance.

Traditionally LDTs have had higher standards because they tend to generate more emissions due to larger displacement engines and the fact that they have typically been operated under high loads. The greatest concern with controlling emissions for LDTs has always been that catalysts couldn't be placed close enough to the engine to reduce cold start emissions because of concerns over thermal damage to the catalyst resulting from the high levels of heat generated by the trucks when under load. But as discussed above, catalysts are now capable of withstanding much higher temperatures, and this is no longer an issue.

Another reason why the emission standards for LDT3s and LDT4s were set so much higher than those for LDVs and lighter LDTs was that the heavier LDTs were tested at adjusted loaded vehicle weight, not loaded vehicle weight. Adjusted loaded vehicle weight is the vehicle's curb weight plus half of its maximum payload capacity. Loaded vehicle weight is the vehicle's curb weight plus 300 pounds. This was done in the past because the LDT3s and LDT4s were believed to be used primarily as cargo carrying vehicles and should be regulated under these conditions. While their weight during emission testing generally increases emissions, the applicable emission standards were numerically increased to compensate for this.

As part of the Tier 2 proposal, LDT3s and LDT4s will be tested like LDVs and the lighter LDTs, at the vehicle's curb weight plus 300 pounds. This change represents the recent trend for these trucks to be used predominantly as passenger carrying vehicles. This change would also reduce the certified emission level of any current LDT3 or LDT4 simply by reducing the amount of fuel the vehicle consumes over the test cycle. Under the proposed test procedure, all current LDT3s and LDT4s would be closer to the design targets for the proposed Tier 2 standards. Likewise, the difference between the current Tier 1 standards for these vehicles and the proposed Tier 2 standards is actually much smaller than a comparison of the numerical standards would indicate.

Overall, several certified and research LDVs have met the design targets for the proposed Tier 2 standards in 1998 with, in many cases, considerable margin to spare. This indicates that significant margin exists with which to accommodate the greater weight and aerodynamic drag of LDT3s and LDT4s when meeting the same design targets. In addition, significant LDT emission



reductions were achieved from vehicles emitting well below the applicable LEV design targets by primarily just changing catalysts (in the case of MECA and ARB) or just changing engine calibration (in the case of Ford). This confirms that the benefits of advanced emission control technology on LDTs has not been exhausted in meeting current LEV emission standards. Overall, these findings indicate that the proposed Tier 2 standards for LDTs should be feasible with the same basic types of emission controls as required by LDVs. The heavier LDTs will likely require somewhat larger catalysts than LDVs and the lighter LDTs and possibly also incorporate a greater number of supporting technologies, such as a low-thermal capacity manifold, in order to meet the same numerical emission standard.

### **c. Lean-Burn Technology**

The above discussion focused on advancements in emission control technology. New gasoline engine designs are also being developed to reduce fuel consumption. In particular, gasoline direct-injection (GDI) engines have been developed (and are being sold in Japan and Europe) which operate on 10-20 percent less fuel than today's gasoline engines.

One of the reasons that these engines use less fuel is that they use much more air than is needed just to burn the fuel. In this respect, they operate similar to a diesel engine. While this is advantageous for fuel efficiency, it makes it more difficult to eliminate NO<sub>x</sub> emission using aftertreatment technology. Highly efficient 3-way catalysts require that there be little excess oxygen in the exhaust stream in order to convert NO<sub>x</sub> emissions to nitrogen and oxygen. Unfortunately, if a GDI engine is operated in this way, nearly all of its fuel efficiency benefits are lost.

A number of potential techniques are being developed to control NO<sub>x</sub> emissions when excess air is present. These techniques are discussed in more detail in Section 5. below. The most promising of these techniques for GDI engines are the lean NO<sub>x</sub> catalyst and the NO<sub>x</sub> adsorber. A GDI engine may be able to meet the highest NO<sub>x</sub> bin of 0.2 g/mi with a lean NO<sub>x</sub> catalyst and 30 ppm sulfur gasoline. However, this is dependent on achieving engine out emissions below 0.4 g/mi, and this is likely to be a very difficult challenge. NO<sub>x</sub> adsorbers are potentially more efficient than lean NO<sub>x</sub> catalysts. Thus, the required engine out NO<sub>x</sub> emission levels are likely to be well within the capability of GDI engine technology. However, the NO<sub>x</sub> adsorber is in an earlier stage of development relative to the lean NO<sub>x</sub> catalyst. Much development work is still necessary in order for this technology to be applied commercially. Also, even 30 ppm sulfur levels degrade long-term performance of NO<sub>x</sub> adsorbers. Thus, either methods to regenerate the NO<sub>x</sub> adsorber onboard the vehicle must be developed or even lower sulfur levels will be required.

## **2. CO Emissions from Gasoline Fueled Vehicles**

EPA is only proposing tighter CO emission standards for LDT2s, LDT3s and LDT4s.

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Basically, CO emissions from these vehicles must be reduced to the levels now required for LDVs and LDT1s under the NLEV program. Also, LDVs and LDTs must comply with the NLEV CO standards over a slightly longer useful life of 120,000 miles instead of the current useful life of 100,000 miles.

Compliance with the proposed Tier 2 CO emission standards should not be difficult given compliance with the proposed Tier 2 NMOG standards. The control of both pollutants utilizes much of the same technology and the proposed Tier 2 NMOG standards are the more stringent of the two sets of standards. In addition, the above mentioned change in test weight should make it even more easy to meet the proposed Tier 2 CO emission standards. The following table IV-10 summarizes CO emissions from vehicles certified to the LEV standards in California.

**Table IV-10. CO Emissions from California LEVs (g/mi)**

<i>LDV/LDT</i>	<i>LDT2</i>	<i>LDT3</i>	<i>LDT4</i>
0.8	1.13	2.35	2.95

As can be seen, the CO emissions from all of these vehicles are well below the proposed Tier 2 CO standard of 4.2 g/mi. While CO emissions from LDT3s and LDT4s are more than half the proposed 4.2 g/mi standard, the current LEV standards for these vehicles is more than twice the proposed Tier 2 NMOG standard of 0.09 g/mi. As NMOG emissions are reduced to meet the 0.09 g/mi standard, CO emissions will decrease further, as well. CO emission control is also not a problem for GDI engines. Thus, compliance with the proposed Tier 2 CO standard should not add any additional burden to manufacturers relative to compliance with the proposed NMOG and NOx standards.

### **3. Formaldehyde Emissions from Gasoline Fueled Vehicles**

EPA is only proposing tighter formaldehyde emission standards for LDT2s, LDT3s and LDT4s. Basically, formaldehyde emissions from these vehicles must be reduced to the levels now required for LDVs and LDT1s under the NLEV program. Also, LDVs and LDT1s would have to comply with the NLEV formaldehyde standards over a slightly longer useful life of 120,000 miles versus the current 100,000 mile useful life.

Again, as with CO emissions, compliance with the proposed Tier 2 formaldehyde emission standards should not be difficult given compliance with the proposed Tier 2 NMOG standards. The control of both pollutants utilizes much of the same technology and the proposed Tier 2 NMOG standards are the more stringent of the two sets of standards. Table IV-11, below, summarizes formaldehyde emissions from vehicles certified to the LEV standards in California.

**Table IV-11. Formaldehyde Emissions from California LEVs (g/mi)**

<i>LDV</i>	<i>LDV/LDT1</i>	<i>LDT2</i>	<i>LDT3</i>	<i>LDT4</i>
0.0012	0.0016	0.0013	0.002	0.002

As can be seen, formaldehyde emissions from current California vehicles are roughly a factor of 10 below the proposed Tier 2 formaldehyde standard of 0.018 g/mi. Thus, compliance with the proposed Tier 2 formaldehyde standard should not add any additional burden to manufacturers relative to compliance with the proposed NMOG and NO<sub>x</sub> standards.

#### **4. Evaporative Emissions**

The standards we are proposing today for evaporative emissions are technologically feasible now. Many designs have been certified by a wide variety of manufacturers that already meet these standards. A review of the 1999 model year certification results indicates that the average family is certified at less than 1.0 grams per test on the 3 day diurnal plus hot soak test, i.e. at less than half the current 2.0 g/test standard.

The standards we are proposing will not require the development of new materials or, in many cases, even the new application of existing materials. Low permeability materials and low loss connections and seals are already used to varying degrees on current vehicles. Today's standards will likely ensure their consistent use and discourage manufacturers from switching to cheaper materials or designs to take advantage of the large safety margins they have under current standards ("backsliding").

There are two approaches to reducing evaporative emissions for a given fuel. One is to minimize the potential for permeation and leakage by reducing the number of hoses, fittings and connections. The second is to use less permeable hoses and lower loss fittings and connections. Manufacturers are already employing both approaches.

Most manufacturers are moving to "returnless" fuel injection systems, and at least one major manufacturer utilizes returnless systems on all of their vehicles. Through more precise fuel pumping and metering, these systems eliminate the return line in the fuel injection system which carries unneeded fuel from the fuel injectors, which has been heated from its close proximity to the hot engine, back to the fuel tank. Returned fuel is a significant source of fuel tank heat and vapor generation. The elimination of return lines also reduces the total length of hose on the vehicle and also reduces the number of fittings and connections which can leak.

Low permeability hoses and seals as well as low loss fittings are available and are already in use on many vehicles. Fluoropolymer materials can be added as liners to hose and component materials to yield large reductions in permeability over such conventional materials as monowall nylon. In addition, fluoropolymer materials can greatly reduce the adverse impact of alcohols in

gasoline on permeability of evaporative components, hoses and seals.

### **5. Diesel Vehicles**

Very few LDVs and LDTs are currently sold with diesel engines. Out of annual sales of more than 15 million vehicles, roughly only 30,000 are equipped with diesel engines. This is in part due to the low price of gasoline over the past decade. Recently, a number of vehicle manufacturers have announced aggressive programs to increase the sales of diesel LDVs and LDTs. These programs are scheduled to begin between model year 2000 and 2002 and appear to be aimed at easing manufacturers' compliance with the corporate fuel economy standards, particularly for LDTs.

NO<sub>x</sub> and PM are the two biggest emission-related challenges for diesel engines. Diesels have inherently low emissions of CO and NMOG and should have no problem meeting the proposed Tier 2 standards for these pollutants. Therefore, the remainder of this discussion will focus on NO<sub>x</sub> and PM.

Considerable progress has been made over the past 10 years in reducing engine-out emissions from diesel engines. In heavy trucks and buses, PM emission standards which were projected to require the use of exhaust aftertreatment devices were met with only engine modifications. NO<sub>x</sub> emissions from heavy trucks and buses sold starting in 2002 will also reflect deep reductions from emission levels typical of engines produced in the mid-1980's. However, the benefits of improved diesel engine design appear to be reaching their limits. EPA projects that diesel LDVs and LDTs could only meet NO<sub>x</sub> emissions standards of roughly 0.5-0.6 g/mi and PM emission standards of roughly 0.05-0.08 g/mi without aftertreatment. These levels are well above the highest allowable certification emission levels included in today's proposal.

In order to comply with the proposed Tier 2 emission standards for NO<sub>x</sub> and PM, diesels will require the use of effective aftertreatment devices. For NO<sub>x</sub> emissions, these devices include lean NO<sub>x</sub> catalysts, selective catalytic reduction (SCR) and NO<sub>x</sub> adsorbers. Lean NO<sub>x</sub> catalysts are still under development and appear capable of reducing NO<sub>x</sub> emissions by 15-30 percent. Therefore, they are unlikely to be sufficiently effective to enable compliance with the proposed Tier 2 standards.

SCR has been demonstrated commercially on stationary diesel engines and can reduce NO<sub>x</sub> emissions by 80-90 percent. However, SCR requires that the chemical urea be injected into the exhaust before the catalyst. This means that vehicle owners would have to periodically refuel their vehicle with urea, as well as diesel fuel. Ammonia emissions also occasionally occur with use of SCR, which has a very objectionable odor.

Finally, NO<sub>x</sub> adsorbers can be up to 90 percent efficient at removing NO<sub>x</sub> from the exhaust. However, these adsorbers are quickly poisoned by sulfur in the fuel and would require reductions in diesel fuel sulfur content. Their use also requires that the engine be run with excess

fuel occasionally, so that the stored NO<sub>x</sub> can be converted to nitrogen and oxygen. These adsorbers, coupled with techniques for introducing fuel into the exhaust periodically are still at the research stage.

Overall, use of either SCR or a NO<sub>x</sub> adsorber should be able to enable compliance with the proposed Tier 2 standards. The issue of reducing diesel fuel sulfur levels to enable NO<sub>x</sub> adsorbers and other technologies is discussed in a separate ANPRM.

Regarding PM, applicable aftertreatment devices tend to fall into two categories: oxidation catalysts and traps. Diesel oxidation catalysts look very similar to the 3-way catalysts used on gasoline vehicles. Diesel catalysts convert the hydrocarbon compounds in the exhaust to water and carbon dioxide. This reduces exhaust NMOG emissions and heavier HC compounds which comprise about 30 percent of total PM mass emissions. The oxidation catalyst can be from 50 percent to 90 percent effective at converting HC. Thus, an oxidation catalyst can reduce total PM emissions by roughly 15-27 percent. By itself, the oxidation catalyst is not likely to be sufficient to enable compliance with the proposed Tier 2 standards without further advancements in engine technology.

Traps can eliminate up to 90 percent of diesel PM emissions. The trap first filters the carbonaceous particles from the exhaust. Then, periodically, this trapped PM must be burned, or the trap will fill up and cause problems in operating the engine. Diesel traps are currently being used on buses in an number of U.S. cities. It appears that these traps can regenerate frequently enough given the operating temperatures of bus engines and over-the-road trucks. However, there is some question whether or not these traps could regenerate frequently enough with the somewhat lower operating temperatures of diesel engines in LDVs and LDTs. Regeneration can be enhanced at lower exhaust temperatures through the use of more active catalysts on the surface of the trap. However, these catalytic materials convert sulfur dioxide in the exhaust to sulfuric acid. Thus, their use requires the removal of most of the sulfur in the fuel. Research indicates that low temperature regeneration may also be enhanced through the use of catalytic fuel additives comprised of cerium or iron. However, particulate containing these chemicals can be emitted from the tailpipe, raising some health concerns. Use of these catalytic fuel additives does not require the removal of sulfur from diesel fuel. An efficient trap should enable compliance with the proposed Tier 2 PM standards.

## **B. Feasibility of Removing Sulfur from Gasoline**

### **1. Source of Gasoline Sulfur**

Sulfur is in gasoline because it naturally occurs in crude oil. Crude oil contains anywhere from fractions of a percent of sulfur, such as less than 0.05 weight percent (0.05 percent is the same as 500 ppm) to as much as several percent.<sup>2</sup> The average amount of sulfur in crude oil refined in the U.S. is about one percent.<sup>3</sup> Most of sulfur in crude oil is in the heaviest part, or in the heaviest petroleum compounds, of the crude oil (outside of the gasoline boiling range). In the

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process of refining crude oil into finished products, such as gasoline, some of the heavy compounds are broken up into smaller compounds and the embedded sulfur ends up in gasoline. Thus, the refinery units which convert the heavy parts of crude oil into gasoline are the units most responsible for putting sulfur into gasoline.

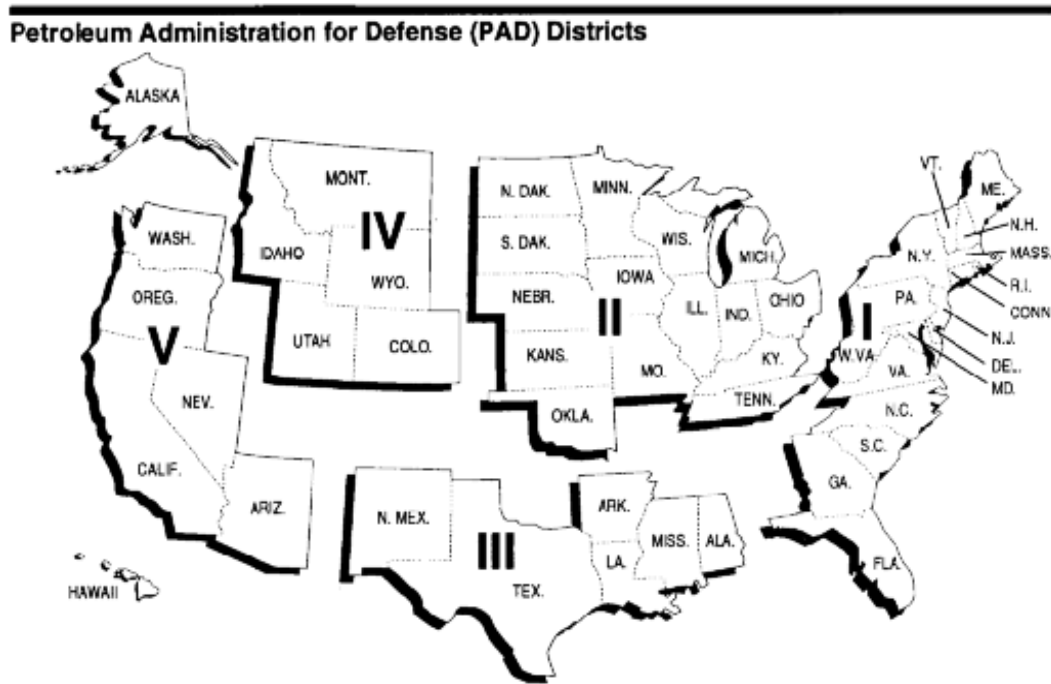
The fluidized catalytic cracker (FCC) unit is the refinery processing unit most responsible for moving sulfur into gasoline. The FCC unit cracks large carbon molecules into smaller ones and produces anywhere from 30 to 50 percent of the gasoline in most refineries. Because the FCC unit makes gasoline out of the heavier, higher sulfur-containing compounds, more than 90 percent of sulfur in gasoline comes from that unit.<sup>4</sup> Another refinery unit which is responsible for a significant amount of sulfur in gasoline is the coker unit. These units produce coke from the heavy part of the crude oil. In the process of producing coke, some gasoline blendstocks are produced and some of these blendstocks are blended directly into gasoline. While the volume of gasoline blendstock produced by the coker is small (normally less than one percent of the gasoline pool), this stream usually contains more than 3000 ppm sulfur,<sup>5</sup> so the contribution of sulfur to gasoline is significant.

Another gasoline blendstock which contributes sulfur to gasoline is the straight run. Straight run is the portion of the crude oil which falls in the gasoline boiling range which is blended directly into gasoline. Usually only the light straight run is blended into gasoline which has a small amount of sulfur (i.e., on the order of 100 ppm sulfur), although in trying to meet a low sulfur standard, even this amount of sulfur becomes significant. The heaviest portion of straight run, which would have more sulfur, is normally desulfurized and reformed in the reformer (to improve its octane), so its contribution to the gasoline pool is virtually nil. Alkylate is another stream which can have enough sulfur worth mentioning. Most refineries have less than five ppm sulfur in this pool, however, some refineries which feed coker naphtha to the alkylate plant can have much more. On average, alkylate probably has about 10 ppm sulfur. Other gasoline blendstock streams with either very low or no sulfur are alkylate, hydrocrackate, and isomerate. Oxygenates which are blended into gasoline usually have no sulfur, however, during shipping through pipelines, they can pick up some sulfur. The implementation of a low gasoline sulfur standard, though, would reduce much of the sulfur which oxygenates could pick up in the pipeline.

Since FCC units and cokers contribute so much sulfur to gasoline, then a reasonable conclusion which could be reached would be that refineries could simply shut down these units to meet a low sulfur standard. This conclusion is not reasonable considering the quality of crude oil which is used today and the products demanded of the oil industry. Much of the volume of crude oil is composed of heavy compounds which has no end use, and thus is not usable without processing by these units. Thus, these units make marketable products from what would otherwise be a waste oil stream.

## **2. Current Levels of Sulfur in Gasoline**

It is important to know the average level of sulfur in gasoline because it helps determine the most effective removal methods which should be used. The American Petroleum Institute (API) and the National Petrochemical Refiners Association (NPRA) surveyed gasoline producers to gather information concerning refining operations during the Summer of 1996.<sup>6</sup> They collected information on the qualities of gasoline for various regions called Petroleum Administrative Districts for Defense (PADDs), as well as for the country as a whole. (These PADDs are illustrated below in Figure IV-2). Their study showed that the gasoline sulfur, outside of California, averaged 340 ppm during the Summer of 1996.



**Figure IV-2. Map of U.S. Petroleum Administrative Districts for Defense**

When looking closer at the information provided in the report, we discovered that some PADD sulfur levels calculated from the API/NPRA data were not in agreement with some of the average blendstock sulfur levels presented within the same report, nor was it consistent with data reported to EPA for the RFG program in 1995 and 1996. One possible reason for the disagreement between the API/NPRA gasoline pool sulfur level and that reported to the RFG data base is that API and NPRA only surveyed refiners for their summertime gasoline qualities. Other possible reasons for the discrepancy are, that some refiners did not participate with the API/NPRA survey (especially in PADDs 1 and 5), while data handling complications also precluded the inclusion of gasoline sulfur data from some refiners from being reported in the RFG data base. However, because the RFG data base contains year-round data and because it often represents a larger portion of the gasoline sulfur pool, when the sulfur levels were compared between the two data bases, or when the API/NPRA information was compared

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internally, and there was disagreement, then the RFG data were used over the API/NPRA survey information. The methodology for adjusting the average sulfur levels is described in more detail below in the section on fuel costs.

After adjusting the sulfur values for each PADD, the national average gasoline sulfur level for domestically produced gasoline is 305 ppm. Table IV-12 below summarizes the U.S. sulfur levels by PADD, and for the country as a whole. Because California has its own low sulfur gasoline program, gasoline produced there was excluded from consideration in this analysis.

**Table IV-12. Average Sulfur Levels by PADD and for the Nation.**

	<i>PADD 1</i>	<i>PADD 2</i>	<i>PADD 3</i>	<i>PADD 4</i>	<i>PADD 5</i> <i>OC*</i>	<i>U.S.</i> <i>Avg.*</i>
Estimated Average Sulfur Levels	215	338	308	265	506	305

\* Outside of California

It is important to note that the gasoline sulfur values reported in Table IV-12 are an attempt to estimate the average gasoline sulfur level for estimating the cost of desulfurization. In actuality, each sulfur value represents the volumetric average of a range of sulfur values with each refinery representing a single data point. This range can vary from the tens of ppm to almost 1000 ppm. The 1000 ppm sulfur level is the upper limit of the amount of sulfur permitted to be shipped in pipelines in accordance with the American Society for Testing Materials (ASTM) consensus standards.<sup>7</sup>

### **3. Feasibility of Meeting the Proposed Gasoline Sulfur Standards**

The feasibility of meeting the proposed standards for low sulfur gasoline can be demonstrated in two distinct ways. The first way is to assess whether there is technology available, or that can reasonably be expected to be available in the lead time provided, to the refining industry to meet the proposed standard. The second way is to determine if refiners are already demonstrating that they can meet a low sulfur gasoline standard similar to this proposed rule. Evidence that refiners are already meeting a stringent gasoline sulfur program is a more compelling example of feasibility since the technology must already be available if low sulfur gasoline is already being produced.

It is indeed the case that there are low sulfur gasoline programs already in place. The State of California requires gasoline sold in the State to meet a 30 ppm gasoline sulfur standard on average and a 80 ppm cap, among a number of other fuel standards.<sup>8</sup> Furthermore, refiners can produce gasoline which varies in composition, provided that the California Predictive Emissions Model (which, like EPA's Complex Model, estimates vehicle emissions from fuels of varying composition) confirms that the proposed fuel formulation meets or exceeds the emissions



reduction that would occur based on the default fuel requirements. California refineries are using the flexibility provided by the Predictive Model to surpass the prescriptive standards for gasoline sulfur and are producing gasoline which contains 20 ppm sulfur on average.<sup>9</sup> They are making this very low sulfur gasoline despite using Californian and Alaskan crude oils which are poorer quality than most other crude oils being used today. Thus, the experience in California demonstrates that commercial technologies already exist to permit refiners to produce low sulfur gasoline.

In addition to the California experience here in the U.S., a low sulfur requirement in Japan provides additional evidence that reducing gasoline sulfur levels to low levels is feasible. Japanese refineries must meet a 100 ppm per-gallon cap. Based on the gasoline sulfur cap established there, gasoline in Japan averages about 20 ppm sulfur.

### **4. Meeting a Low Sulfur Gasoline Standard**

The methodology that would be used refiners to lower their sulfur level depends on a number of factors specific to their refinery. These factors include:

- The gasoline sulfur level prior to the start of the gasoline sulfur program
- The refinery configuration (A typical complex refinery is illustrated in Figure IV-3, below.)
- The amount of excess refinery desulfurization equipment on hand
- The quality of feedstocks available, especially crude oil
- The quality and types of products produced
- Any plans to change the feedstocks or products of the refinery
- The desulfurization technologies available and their cost
- Other regulatory programs affecting refinery operations in the same time frame

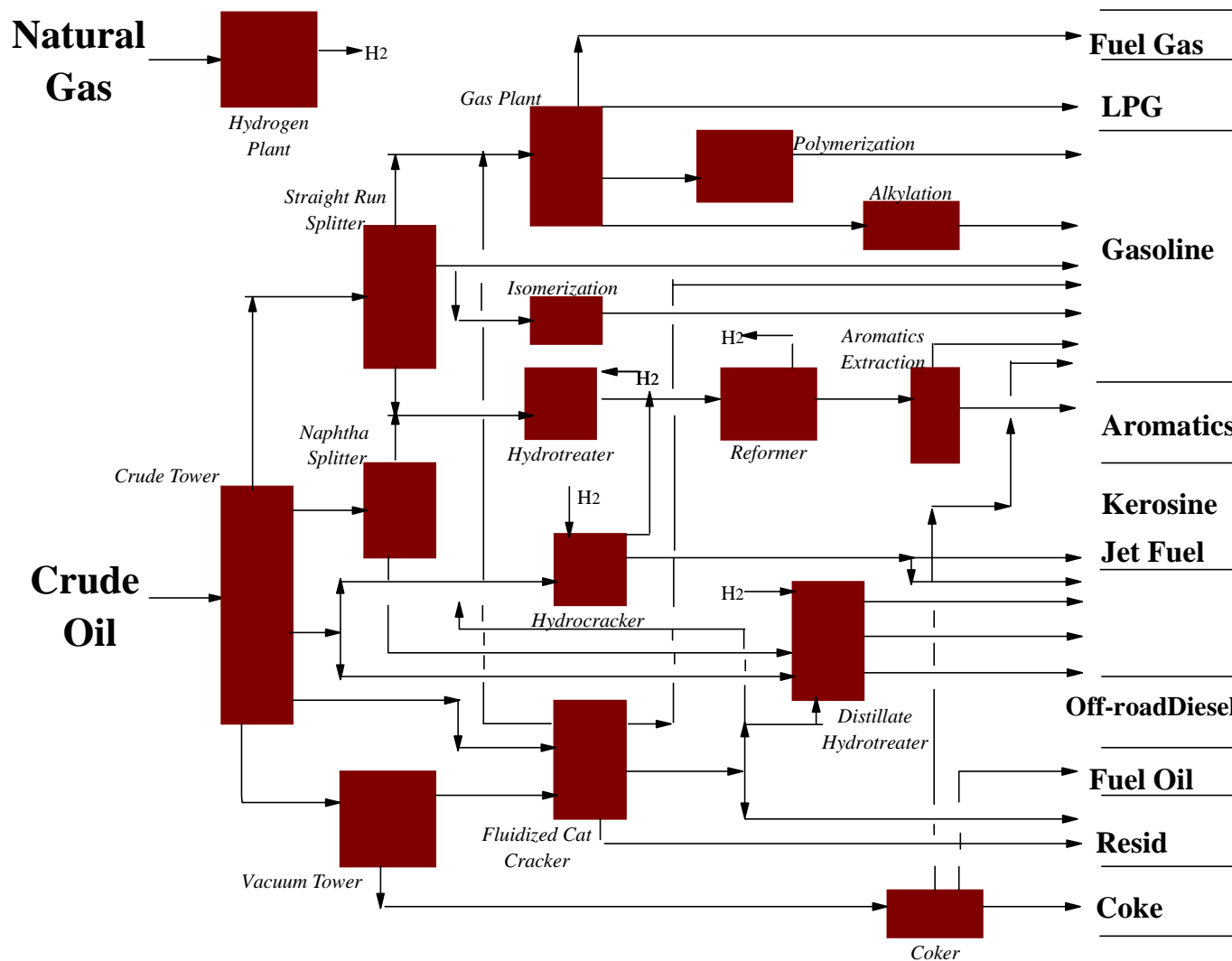


Figure IV-3. Diagram of a Typical Complex Refinery

A refinery's average gasoline sulfur level is the most important factor determining whether a refiner would need to make a substantial capital investment to meet a sulfur standard. After numerous discussions with refiners, we believe that those refiners with low gasoline sulfur levels to begin with (i.e., gasoline sulfur levels lower than, perhaps, 60 ppm) will probably not need to invest in expensive capital. These refineries have such low sulfur levels due to one or more of a number of possible reasons. For example, some of these refiners may not have certain refining units, such as a fluidized catalytic cracker (FCC) unit, or a coker, which convert heavy boiling stocks to gasoline (Figure IV-3 shows where these units are placed in a refinery). As stated above, these units push more sulfur into gasoline and their absence means less sulfur in gasoline. Alternatively, refiners may use a low sulfur (sweet) crude oil, which results in lower sulfur gasoline. Or, these refiners may have already installed a hydroprocessing unit, such as FCC feed hydrotreating, to improve the operations of their refinery which uses a heavier, higher sulfur (more sour) crude oil. This unit removes much of the sulfur from the heaviest portion of the heavy gas oil before it is converted into gasoline.

Of the refiners in this first category, the refineries with sulfur levels below the proposed sulfur standard would not have to do anything. On the other hand, those refineries with sulfur levels above the proposed standard, but below some level, such as 60 ppm, could probably meet the standard employing operational changes only, which means avoiding capital investments if this is desirable. For example, these refiners may be able to meet the proposed sulfur standard by running existing desulfurization units harder, at capacity if the unit has headroom, or by debottlenecking the unit, perhaps by using more effective catalyst. Alternatively, these refineries may be able to meet the proposed sulfur standard by using a slightly sweeter crude oil. Refiners also have FCC additives available to them which could allow them to reduce their FCC gasoline sulfur level by 15 to 35 percent.<sup>10</sup> Another strategy that these refiners could use to meet the proposed gasoline sulfur standard would be to undercut the FCC gasoline. By cutting out the heaviest 10 volume percent of FCC gasoline and sending that part to on-road diesel before hydrotreating, to off-road diesel or to heating oil, refiners would be able to cut out 40 percent or even more of the sulfur from this high sulfur blendstock. However, the refiners which choose to undercut their FCC gasoline would then produce less volume of gasoline which generally provides the highest profit margin. For this reason undercutting the FCC gasoline would likely be a short term strategy. Finally, these refinery may be able to meet the sulfur standard by blending in low sulfur oxygenates. Refiners may be able to employ several of these desulfurization strategies together in varying degrees. These refiners with very low gasoline sulfur levels to begin with produce only a small portion of the gasoline consumed in this country, on the order of five percent.<sup>11</sup>

The vast majority of gasoline is produced by refineries with higher sulfur levels, and refiners are expected to install capital equipment in these refineries to meet the proposed gasoline sulfur standard. As stated above, the FCC unit is responsible for most of the sulfur in gasoline. Thus, investments for desulfurizing gasoline would likely involve the FCC unit to maximize the sulfur reduction, and to minimize the cost. This desulfurization capital investment can be installed to treat the gas oil feed to the FCC unit, or treat the gasoline blendstock which is

produced by the FCC unit. Each method has advantages and disadvantages.

FCC feed hydrotreating can be accomplished by a hydrotreater or a mild hydrocracker. These units are designed to operate at high pressures and temperatures to treat a number of contaminants in gas oil. Besides sulfur, FCC feed hydrotreating also reduces nitrogen and certain metals such as vanadium and nickel. These nonsulfur contaminants adversely affect the FCC catalyst, so the addition of this unit would improve the yield of higher profit-making products such as gasoline and diesel. While FCC feed hydrotreating provides these benefits which partially offsets the costs of adding this type of desulfurization, the costs are still high enough that many refiners would have a hard time justifying the installation of this sort of unit. For a medium to large refinery, the capital costs may exceed \$100 million. Because of the higher temperatures and pressures involved, operating costs are expensive relative to other forms of hydrotreating explained below. Refiners may be better able to justify this approach if they switch to a heavier, more sour crude oil. These crude oils are less expensive per barrel and can offset the increased cost of the FCC desulfurization unit, providing that the combination of reduced crude oil costs and higher product revenues justify the switch. Another benefit for using FCC feed hydrotreating is that the portion of the distillate pool which comes from the FCC unit would be hydrotreated as well. While this distillate blendstock, termed light cycle oil, comprises a relatively small portion of the total distillate produced in the refinery (about 20 percent of on-road diesel comes from light cycle oil), like gasoline, it contributes a larger portion of the total sulfur which ends up in distillate. Thus, FCC hydrotreating would allow a refiner to produce more low sulfur onroad diesel or meet a lower sulfur standard for onroad diesel, which could apply in the future.

A less expensive alternative to hydrotreating the FCC feed for gasoline desulfurization is FCC gasoline hydrotreating. FCC gasoline hydrotreating only treats the gasoline produced by the FCC unit. Understandably, this unit is much smaller because only about 60 percent of the feed to the FCC unit ends up as gasoline produced by the FCC unit. The unit is often smaller than that as refiners typically only treat the heavier, higher sulfur portion of that stream. FCC gasoline hydrotreaters operate at lower temperatures and pressures as well which further reduces the capital and operating costs associated with this type of desulfurization equipment. For a medium to large refinery, the capital costs would be on the order of \$50 million for a conventional hydrotreater. One drawback of this process is that octane value and some of the gasoline yield is lost during desulfurization. The loss of this octane must be made up by additional octane production by other units in the refinery or by oxygenate addition, and the volume loss can be made up by additional throughput to gasoline producing units, or also by oxygenate addition.

The loss of octane and gasoline yield caused by FCC gasoline hydrotreating is much lower with gasoline desulfurization technologies which were recently introduced. CDTECH and Mobil Oil each have developed new or improved technologies for desulfurizing gasoline. CDTECH calls its two hydrotreating units for treating FCC full range gasoline CDHydro and CDHDS. Mobil Oil calls its process OCTGAIN 220. These processes preserve much of the octane and gasoline yield because they were designed for treating gasoline blendstocks. One reason why these processes preserve octane and yield is that they operate at lower temperature

and pressure compared to conventional hydrotreating processes. The less severe conditions also lowers the capital and operating costs for this process. The capital cost for these improved processes ranges from \$20 to \$40 million for a medium to large sized refinery. While the capital costs are somewhat less than conventional hydrotreaters, much more cost savings arise out of the reduced utility and ancillary costs. For example, because these processes are less severe, there is much less saturation of olefins, which means that there is much less hydrogen used. Less olefin saturation also translates into less octane loss which would otherwise have to be made up by octane boosting processing units in the refinery.

While these improved gasoline desulfurization technologies have been in the limelight for over a year now, we have also learned that other desulfurization processes are under development. In conversations with several refiners, they shared with us that they are in the process of developing their own desulfurization technology. We would expect them to use their technologies if their development work is completed in time. Furthermore, other refining process licensing firms shared with us that they are developing their own desulfurization technology. We recently became aware that biodesulfurization, which is the removal of sulfur from petroleum using biological means, is on the verge of commercialization for the desulfurization of diesel.<sup>12</sup> The vendor of this technology informed us that the process will be set up and running in about two years in a Petrostar refinery in Alaska. The vendor also shared that gasoline desulfurization is a little further behind, and they believe that they could be ready to market that process for desulfurizing gasoline within the next two years. Two important advantages of this technology are that hydrogen is not needed and that the feed to the unit does not need to be heated to high temperature and compressed to high pressures. The cost savings of these benefits are offset, though, by the need for extensive mixing to maintain an oxygen-rich environment for the bacteria to work effectively. We anticipate that this processes will receive much more attention in the near future as the vendor completes its initial pilot plant work. Our initial assessment is that this process, given time, may be cost competitive with any of the improved gasoline desulfurization technologies. However, at this time, we are only focusing on the improved gasoline desulfurization technologies for which we were given cost information that allowed us to estimate the cost of gasoline desulfurization.

### **5. Improved Gasoline Desulfurization Technology**

We will briefly describe the improved gasoline desulfurization technologies below, but first we'll describe conventional desulfurizing technology to establish a point of reference. Conventional desulfurization occurs in a fixed bed reactor.<sup>13</sup> The reactor is termed fixed bed because a catalyst, which helps to improve the reaction rate and specificity, is contained in a stationary bed within the reactor. The high sulfur gasoline blendstock is heated to a high temperature (on the order of 600 degrees Fahrenheit) and pressure, to maintain the stream as a liquid, and is combined with hydrogen before it enters the reactor. The reactions occur over the bed of the catalyst. While the petroleum is in contact with the catalyst in the reaction vessel, the sulfur is removed from the petroleum compounds and is converted to hydrogen sulfide. Also, most or all of the olefin compounds which are present in the cracked stream are saturated. Since

olefin compounds are much higher in octane than their saturated counterparts, their saturation causes a significant octane loss in any stream with a high olefinic content. Conventional hydrotreating has generally been used for streams with little or no olefins, such as for virgin gas oil which is treated by the FCC unit, or for feed streams to the reformer and isomerizer. Thus, octane loss upon hydrotreating these streams is not a problem. However, FCC gasoline is very rich in olefins such that hydrotreating this stream normally causes a large reduction in octane (up to 8 octane numbers units can be lost if the entire FCC gasoline stream is treated). The saturation of olefins also substantially increases the need for hydrogen.

The catalyst also tends to cause some of the petroleum compounds to “crack, ” converting them from gasoline boiling range compounds to compounds too light for keeping in gasoline, which is termed yield loss. After the reactor, the gaseous compounds, which include unreacted hydrogen, hydrogen sulfide, and any light end petroleum compounds which may have been produced in the reactor, are separated from the liquid compounds. The hydrogen sulfide must be stripped out from the other compounds and then converted to elemental sulfur which is then sold off. If there is enough hydrogen and it can be economically recovered, it is separated from the remaining hydrocarbon stream and recycled. Otherwise it is burned with the light hydrocarbons as fuel gas.

Mobil Octgain will be discussed next since the process is similar to a conventional hydrotreater. This gasoline desulfurization process is the third generation of this process for Mobil, and it is called Octgain 220. Like a conventional hydrotreater, Mobil uses a fixed bed of catalyst for its Octgain process.<sup>14</sup> One primary difference between Octgain and conventional hydrotreating is that Mobil Oil has developed its own catalyst for the reactor. The catalyst not only causes the desulfurization of petroleum, it also causes isomerization reactions to occur (straight chain petroleum compounds are changed to branched chain compounds) which increases the octane of the resultant stream.<sup>15</sup> The octane improvement caused by the catalyst compensates for octane loss resulting from olefin saturation. Mobil designed this generation of Octgain process to operate over a range in severity. If less desulfurization is needed, then the process temperature and pressure are reduced. The less severe operating conditions reduces the saturation of olefins, which in turn reduces less hydrogen consumption and utility use, in addition to causing less octane loss. Under the less severe conditions, much or all of the octane loss can be made up by the isomerization reactions caused by the catalyst. The less severe operating conditions also causes less yield loss, as the conditions are less favorable for causing cracking of the larger petroleum compounds to smaller compounds. Most of these benefits would be negated if extensive desulfurization, on the order of 99 percent, is necessary. The steps of the process following the reactor are the same for conventional FCC gasoline hydrotreaters. One advantage of the Octgain process is that the reactor vessel for the process is the same as vessels used for conventional hydrotreating. Thus, refiners can save on capital costs by using a spare hydrotreating unit which it may have on hand in the refinery.

The CDTECH process is significantly different from either conventional hydrotreating or Octgain, which makes it a little more complex to describe. The CDTECH process utilizes catalytic distillation.<sup>161718</sup> Catalytic distillation is a technology which has been applied for a

number of different purposes. CDTECH is currently licensing the technology to produce MTBE and selective hydrogenation processes. Based on their experience and success with that process, they applied the same technology to desulfurizing gasoline. As the name implies, distillation and desulfurization, via a catalyst, take place in the same vessel. This design feature may save the need to add a separate distillation column in some refineries. All refineries have a distillation column after the FCC unit (called the main fractionation column) which separates the gasoline from the most volatile components (such as liquid petroleum gases), the distillate or diesel (light cycle oil), and the heavy ends or residual oil. However, if a refiner only wishes to treat a portion of the FCC gasoline, then he may have to add a second distillation column to be able to separate off the portion of the FCC gasoline which he wishes not to treat. With the CDTech process, the refiner can choose to treat the entire pool or a portion of the pool, but choosing to treat a part of the pool can be an option in how the CDTech hardware is applied, thus negating any need for an additional distillation column. The choice is realized by setting up the distillation and associated catalyst to treat only the portion of the pool which needs to be treated.

The most important portion of the CDTech desulfurization process is two distillation columns loaded with desulfurization catalyst in a packed structure. The first vessel, called CDHydro, treats the lighter compounds of FCC gasoline, while the second column, called CDHDS, treats the heavier compounds of FCC gasoline. All of the FCC gasoline is fed to the CDHydro column. The five- and six-carbon petroleum compounds boil off and head up through the catalyst mounted in the column, along with hydrogen which is also injected in the bottom of the column. The reactions in this column are unique in that the sulfur in the column are not hydrotreated to hydrogen sulfide, but they instead are reacted with dienes in the feed to form thioethers. Their higher boiling temperature causes the thioethers to fall to the bottom of the column. They join the heavier petroleum compounds at the bottom of the column and sent to the CDHDS column. Because the pressure and temperature of the first column is much lower than conventional hydrotreating, saturation of olefins is reduced to very low levels (according to CDTECH, the saturation which does occur is desirable to eliminate diolefins). Thus, little excess hydrogen is consumed. An option for the refiner is to put in an additional catalyst section in the CDHydro column to increase octane. This octane enhancing catalyst isomerizes the some of the olefins which increases the octane of this stream by about three octane numbers.

The seven-carbon and heavier petroleum compounds leave the bottom of the CDHydro unit and are fed into the CDHDS column. There, the heavier compounds head down the column, and the lighter compounds head up. Both sections of the CDHDS column have catalyst loaded into them which serve as hydrotreating reaction zones. Similar to how hydrogen is fed to the CDHydro column, hydrogen is fed to the bottom of the CDHDS column.

The temperature and pressure of the CDTech process columns are lower than Mobil Oil's Octgain process. These operating conditions minimize yield and octane loss. While the CDTech process is very different from conventional hydrotreating, the catalyst used for removing the sulfur compounds is the same. Thus, if concerned about the reliability of the process, refiners can look at the track record of the catalyst in conventional hydrotreating to get an indication of its expected life, and then adjust that expectation based on the milder conditions involved. One

important difference between the CDTech process and conventional hydrotreating is that CDTech mounts its catalyst in a unique support system, while conventional catalyst is simply dumped into the fixed bed reactor. Although the CDTech desulfurization process is different from conventional hydrotreating processes, the use of a distillation column as the basis for the process is very familiar to refiners. Every refinery has distillation in its refinery, thus, refiners are very skilled in its application.

### **6. Expected Desulfurization Technology to be Used by Refiners**

If the proposed gasoline sulfur standard is finalized, refiners which produce gasoline would have to meet the standard to be able to continue participating in the U.S. gasoline market. As stated above, most refiners will have to invest in desulfurization technology. Arguably, refiners would try to minimize the cost to their business. As stated above, the improved gasoline desulfurization technology costs of CDTECH and Mobil Oil Octgain provide refiners a lower cost option for meeting a gasoline sulfur standard. However, many refiners have shared with EPA that they may be hesitant to use these improved, but recently developed technologies for gasoline desulfurization. They claim that until the technologies have been installed in one or more refineries and operated for a while, that there will continue to be a significant measure of uncertainty. This uncertainty could tip the balance away from using these improved desulfurization technologies, to applying more expensive conventional desulfurization technology.

While there is a concern now on the part of some refiners about using these improved, but not commercially tested desulfurization technologies, we believe that much of this concern will dissipate shortly. Both processes are expected to be installed and operated in refineries later on this year. Mobil Oil has an Octgain hydrotreater installed at its Joliet, Illinois refinery. Up to now, though, only the second generation Octgain catalyst (Octgain 125) was demonstrated at that site. However, Mobil Oil plans to load its new Octgain 220 catalyst in the hydrotreater at Joliet to determine how it runs in a full scale hydrotreater. This experience should start to occur sometime before midyear of 1999.<sup>19</sup> CDTech has years of accumulated service with its CDHydro unit. In its present service, certain olefins called dienes are reduced and octane is improved. While this service is not intended for desulfurization, these units do in fact combine sulfur compounds together much like how the process will operate in a desulfurization service. Thus, this unit has extensive operational experience already. The CDHDS unit, on the other hand, has not been installed in any refinery. It is to be installed in a Motiva refinery (which was Star) in Port Arthur, Texas, with a start-up date sometime around the third quarter of 1999. Another refinery, which is Transamerican in Louisiana, is also planning to install the CDHDS unit, followed by the CDHydro unit for desulfurization, sometime in the first half of the year 2000.

### **7. Feasibility for a Low Gasoline Sulfur Standard in 2004**

We believe that sufficient evidence exists which supports the conclusion that it is feasible



for the U.S. refining industry to meet the 30 ppm average standard in four years or less. We discussed the possibility of meeting a stringent gasoline sulfur program with refiners. The American Petroleum Institute (API) communicated to us that a minimum of four years is needed between when a fuel regulatory requirement is promulgated and when the requirement must be implemented.<sup>20</sup> In API's comments on this issue, it provided a schematic of a typical refinery project development timeline. This schematic showed that a "best estimate" of installation time would be 4.5 years. However, if contingencies are considered, then 5 years would be required. In more detail and without contingencies, API's project timing schedule without contingencies is summarized here relative to date of the final rule (FR). The table also shows EPA's estimates for the same process steps.

**Table IV-13. Leadtime Required Between Promulgation of the Final Rule and Implementation of the Gasoline Sulfur Standard (years)**

	EPA		API (without contingencies)	
	Time for Individual Step	Cumulative Time	Time for Individual Step	Cumulative Time
Scoping Studies	0.5-1.0*	0.5	1.5*	1.0
Process Design	0.75-1.5	1.25-2.0	1.5	2.0
Permitting	0.5-1.0	1.75-2.5	1.5	2.5
Detailed Engineering	0.5-1.0	2.0-3.0	1.25	2.75
Field Construction	0.75-1.25	2.25-3.5	1.5	4
Start-up/Shakedown	0.25-0.5	2.5-4.0	0.75	4.5

\* Can begin before FRM

Scoping and screening studies refer to the process whereby refiners investigate various approaches to sulfur control. These studies involve discussions with firms which supply gasoline desulfurization and other refining technology, as well as studies by the refiner to assess the economic impacts of various approaches to meeting the sulfur standard. In the case of gasoline desulfurization, a refiner would likely send samples of their FCC gasoline to the firms marketing gasoline desulfurization technology to determine how well each technology removed the sulfur from that particular type of FCC gasoline (e.g., sulfur removal efficiency, octane and yield loss, hydrogen consumption, etc.).

API projects that these studies can start 6 months prior to the final rule and would continue for a year after the final rule. Based on discussions with both refiners and technology providers, it is clear that many refiners have already been conducting these studies for at least a year. We believe that by the time of the final rule, refiners will already have a very good idea of the performance and economics of the various gasoline desulfurization technologies at the pilot

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plant level. Some time will be required to process the details of the final rule. More importantly, however, is that many of the new gasoline desulfurization technologies will be demonstrated in actual refinery applications this year. Refiners naturally desire as much demonstrated experience with any new technology as possible prior to investing significant amounts of capital in these technologies. As discussed above, we believe that these new technologies are sufficiently similar to existing gasoline desulfurization technology that long-term performance will not be an issue if the process operates as designed initially. Thus, we believe that sufficient performance data will be available within 6 months after the final rule to allow refiners to initiate process design. This is the same time period estimated by API, though API estimates that the scoping studies will extend 6 months into the process design period.. As this does not affect the total leadtime needed, the ability to modify the design during the process design period simply gives a refiner more flexibility to optimize its design.

API then estimates that process design, permitting and detailed engineering will require almost two and a half years. While not shown in the table, API estimates that the major appropriation decision will be made two and a half years into the process, or just after receiving the final permit approval and just before detailed engineering is completed.

The time required for process design will depend on the extent of the refinery modifications planned. We expect that the great majority of refiners will hydrotreat their FCC gasoline. If no existing equipment is used, this primarily involves building the hydrotreater and its associated equipment (distillation columns, furnaces, pumps, compressors). The refiner would also require a source of a hydrogen for the desulfurization unit. This could come from hydrogen already being generated in the refinery, or from an outside source. In the extreme, the refiner would have to build its own hydrogen plant. Finally, the refiner will have to ensure that the hydrogen sulfide being generated from the desulfurization equipment can be processed in the refinery's existing sulfur recovery plant. Given the small amount of sulfur being removed from gasoline compared to the amount of sulfur already being processed in the refinery, this is likely to be possible with little change to the sulfur recovery plant. However, some expansion could be required in the extreme.

All of this equipment is already common to refineries. Gasoline desulfurization units are either very similar to existing distillation columns or gasoline and diesel fuel hydrotreaters already being used in essentially every refinery. Hydrogen plants are widely used throughout the refining and chemical industries and can be purchased from vendors as basically stand alone units. The same is true for sulfur recovery plants. Also, design and construction time has been reduced by up to 40 percent between 1991 and 1996 alone by computerized design and improving construction scheduling using state of the art methods.<sup>21</sup> For example, CDTECH estimates that 10 - 12 weeks are needed for the basic process design of their equipment. While this estimate for basic process design may not represent all the technologies which may be used, even if the process design for these other technologies is 2 or even three times longer, this time would still be significantly less than API's estimate. API does not mention any recent reductions in required project schedules associated with computerization and standardization in design and construction improvements. They do make comparisons to past leadtimes provided for RFG, but

only indicate that the leadtime required has increased, not decreased. Thus, it is not clear why API is estimating the need for so much more time for process design and engineering.

It is possible that some refiners might decide to implement more major changes to the refinery, such as adding a FCC feed hydrotreater. This equipment is more unique to each refinery and could require some additional time to design. However, this equipment would significantly reduce a variety of emissions from the FCC unit. This should ease permitting and compensating for any emission increases elsewhere in the refinery. The upper limits of our estimates shown in Table IV-13 apply to the limited number of these more major modifications which might occur.

API also indicates that the time necessary for permitting has increased even since the mid-1990's when refineries made modifications for RFG production. EPA recognizes that permitting is a necessary step in the process and that it is often outside of the refiner's control. EPA has committed to working with states and local agencies to streamline this process as much as possible. We believe that the permitting can be reduced to as short as six months and to at most a year.

According to a general estimate for construction time for about the 1980 time frame, 18 to 42 months should be allowed for large construction projects over \$10 million, which could range up to the installation of an entire refinery or plant.<sup>22</sup> Smaller projects are projected to require substantially less time. The projected capital cost of gasoline desulfurization is near the lower end of the cost range cited, considering inflation. Thus, the 18 month estimate should be considered applicable, which is the same as API's estimate. However, this estimate was well prior to the 35-40% reductions cited above. Also, the construction time for those refiners planning to install demonstration units of the advanced desulfurization technology are well below 18 months. Thus, we estimate the time of construction to be a year, plus or minus three months.

Overall, shortening the permitting and basic process design has a dramatic impact on API's estimated four year time for complying. Based on this analysis, we estimate that refiners should be able to complete the process of designing and installing gasoline desulfurization hardware, and make other refinery changes, in about 2½ to four years. Again, the upper end of this range should only apply to a small number of refiners which will be making major changes to their refinery configuration as a result of gasoline desulfurization.

API estimates that up to an additional year is needed for contingencies. Those refiners which would need that extra time will have added flexibility to meet the proposed program implementation date by participating in the averaging, banking and trading program. Those which can meet the proposed implementation date sooner will be able to generate credits which can be traded to those which need more time to comply. For those refiners which would like to install their own gasoline desulfurization processing units, but are not yet very far along, the trading program would potentially allow them more time to develop their processes.

Several different fuel programs already in place suggest that a stringent gasoline

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desulfurization program can be phased-in sooner than what API claims. The California sulfur control program which was promulgated in June of 1975, started to phase in only six months after promulgation, and was fully phased in 4½ years later.<sup>23</sup> Similarly, the Phase II California Reformulated Gasoline Program was promulgated in November 1991 and took effect about 4½ years after promulgation.<sup>24</sup> However, in addition to a stringent sulfur control standard, refiners also had to meet stringent controls for aromatics, olefins, Reid vapor pressure, and distillation index. Thus, if California refiners began to meet the low sulfur program within six months, and the very stringent RFG requirements in 4½ years, then, this argues that if only a stringent gasoline sulfur standard were to be finalized, that most refiners should be able to meet that requirement in less than four years. Also, because the refining industry already has extensive experience with meeting the California low sulfur requirement, it likely could meet a similar standard sooner.

The On-Road diesel sulfur rulemaking provides an example of refiners meeting a much shorter compliance period. Refiners nationwide met the on-highway low sulfur diesel standards in three years time; since the rulemaking was promulgated August 1990 and took effect October 1993.<sup>25</sup> That rulemaking required refiners to reduce diesel sulfur levels from over 2000 ppm down to under 500 ppm. Diesel hydrotreaters are fixed bed hydrotreaters which, as described above, are essentially the same design as Octgain units

For the Reformulated Gasoline Program, EPA proposed to give refiners 4 years to meet the Complex Model requirements of the Reformulated Gasoline program. We felt that 4 years was necessary so that refines could take time to understand how to most cost-effectively use the Complex Model, and to install whatever capital which needed to be installed. However, this rulemaking specifies a single specification and not require the use of a complex emissions model.

Refiners will have a minimum of four years leadtime to comply with the gasoline sulfur standard if the final rule is promulgated by the end of 1999. However, the sulfur averaging banking and trading program provides up to an extra two years for those refiners participating in the program. Thus, the leadtime provided in this proposal should be sufficient, with one exception.

Small refiners may need more time to comply with a sulfur control program. Small refiners generally have a more difficult time obtaining funding for capital projects, and must plan further in advance of when the funds are needed. We contracted a study of the refining industry which included assessing the time required for small refiners to obtain loans for capital investments. The simple survey revealed that small refiners would need two to three months longer than large refiners to obtain funding. If small refiners are forced to or prefer to seek funding through public means, such as through bond sales, then the time to obtain funding could be longer yet, by up to one third longer.<sup>26</sup> In addition, because of the more limited engineering expertise of many small refiners, the design and construction process for these refineries is relatively more difficult and time consuming. We also think that the contractors which design and install refinery processing units will likely focus first on completing the more expensive

upgrade projects for large refiners. Thus the design and construction of desulfurization hardware in the refinery would take longer as well. For this and other economic reasons, we are proposing to delay the implementation of the low sulfur program for small refiners.

### **8. Phase In of Compliance with the Proposed Sulfur Standards**

In the previous section, we estimated that it would take 2.5-4 years (30-48 months) to design and construct sulfur desulfurization equipment. The lower end of this range was more relevant to those refiners choosing to desulfurize FCC gasoline, while the upper end of the range would more likely apply to more significant changes, possibly involving the construction of a FCC feed hydrotreater and changes to other units in the refinery to accommodate a change in crude oil which the FCC feed hydrotreater enabled.

The proposed gasoline sulfur requirements begin on October 1, 2003. On October 1, 2003, the per gallon cap of 300 ppm takes effect, followed by similar caps of 180 ppm and 80 ppm which take effect on January 1, 2005 and January 1, 2006, respectively. Also, refiners' actual gasoline production must contain less than 120, 90 and 30 ppm sulfur on average during calendar years 2004, 2005 and 2006 (and beyond). Finally, refiners must also meet a refinery average sulfur standard of 30 ppm starting on January 1, 2004.

Between January 1, 2004 and December 31, 2005, the 30 ppm refinery average standard can be met using credits generated or purchased. Between January 1, 2000 and December 31, 2003, credits can be generated by selling gasoline (conventional or reformulated) that contains no more than 150 ppm sulfur. The credit is the difference between the sulfur content of the fuel produced and the refinery's 1997-1998 sulfur baseline in the case of conventional gasoline or wintertime RFG, multiplied by the volume of gasoline produced. In the case of summertime RFG, the credit is the difference between the sulfur content of the fuel produced and 150 ppm, again multiplied by the volume of gasoline produced. Starting in 2004, credits (and debits) are the product of the difference between the sulfur content of the fuel produced (whether conventional or reformulated) and 30 ppm.

The phase in of both the per gallon sulfur caps and the actual average sulfur standards between 2004 and 2006 and the ability to generate sulfur credits starting in 2000 is intended to allow refiners to stagger their investment in desulfurization technology while protecting Tier 2 vehicles from unreasonable sulfur levels and getting substantial emission reductions from both Tier 2 and existing vehicles. In order to estimate the rate at which individual refineries must install desulfurization equipment, we estimated each refinery's current sulfur level and compared this to the proposed requirements. We based our estimates of refinery's current sulfur levels on these refinery's official 1990 baselines, which were developed in support of the EPA's RFG and antidumping programs. These 1990 baselines were updated using 1997 data which refiners submit, again as part of the RFG and antidumping programs. When the 1997 data were available for an individual refinery, it was used in lieu of the 1990 baseline. However, in some cases, 1997 data were only available for all of a corporation's refineries on an aggregate basis. In this case,

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each refinery's 1990 sulfur level was multiplied by the ratio of the refiner's 1997 corporate average sulfur level to its 1990 corporate average sulfur level. This procedure assumes that any change in sulfur between 1990 and 1997 occurred proportionately at each refinery. In a few cases, 1997 data were not yet available for a specific refiner, so the 1990 baseline was used unchanged.

We used these sulfur estimates along with estimates of each refinery's gasoline production to develop a profile of the industry. We grouped refineries by current sulfur level and determined the amount of gasoline produced by non-California refineries in each sulfur grouping. Refiners meeting the definition of a small business were also excluded, as they would have more time to comply with the proposed sulfur requirements than other refiners. The results of this analysis are shown in Table IV-14.

**Table IV-14. Distribution of Refineries by Current Gasoline Sulfur Level**

	<i>Refinery Groupings</i>			
	1	2	3	4
Range of Gasoline Sulfur (ppm)	0-40	41-180	181-300	>300
Average Baseline Sulfur (ppm)	17	105	246	476
Percentage of total fuel produced	2%	26%	26%	47%
Number of Refineries	10	33	25	39

Starting with this information, we projected the actions which refiners could take in meeting the proposed gasoline sulfur requirements. This analysis revealed that the per gallon caps of 300 and 180 ppm applicable nominally in 2004 and 2005 were the most constraining features of the proposal in these early years of the program. Thus, this discussion will begin with compliance with those caps, followed by a discussion of compliance with the absolute corporate average standards of 120 and 90 ppm in 2004 and 2005 and compliance with the 30 ppm standard, which can be met with credits.

A refiner can take two basic types of actions to meet the 2004 and 2005 sulfur caps. It can make operational changes without adding or substantially modifying its current refining equipment or, it can add new capital equipment. Operational modifications include switching to a low sulfur crude oil, operating existing FCC feed and naptha hydrotreaters more severely, debottle-necking these units to process more volume, and shifting the heaviest portion of FCC gasoline (which contains a disproportionate share of FCC gasoline sulfur) to the distillate pool. As an alternative to the last approach, a refiner could hydrotreat this heavy FCC gasoline in its distillate hydrotreater, desulfurize it, separate it from the hydrotreated distillate and then reblend the desulfurized FCC gasoline back into the gasoline pool. We believe that these techniques would enable refiners to reduce sulfur levels in the near term. However, the degree of this reduction is difficult to estimate. Also, refiners have to meet the Phase 2 requirement of the RFG program in 2000, which is generally expected to require RFG to contain roughly 150 ppm sulfur during the summer months.

Very few refiners have built new gasoline desulfurization equipment in order to meet this requirement. Thus, they appear to be planning to meet the 150 ppm level with operational changes or by reblending. Reblending would involve the production of two distinct gasolines within the refinery, one with lower sulfur levels for the RFG market and another gasoline with higher sulfur levels for the conventional gasoline market. The antidumping requirements which apply to non-RFG gasoline implicitly limit the degree to which this can occur, but it still possible that many refiners will use blending strategies to at least partially meet the Phase 2 RFG requirements. In any event, the Phase 2 RFG requirements are likely to utilize some of refiner's existing ability to reduce gasoline sulfur without new capital equipment. This, plus the uncertainty in the degree that operational changes can reduce sulfur levels, led us to believe that refiners would not rely on operational changes as the primary means of meeting the 2004 and 2005 per gallon sulfur caps of 300 and 180 ppm. As a result of this, for the purpose of this analysis, we assumed that any major reductions in gasoline sulfur needed to meet the per gallon caps, as well as the eventual 30 ppm standard, would be met through the construction of new desulfurization equipment.

This uncertainty in the way in which refiners will meet the Phase 2 RFG requirements also led us to assume that the pool average sulfur level will not decrease in 2000 due to these requirements. In fact, some reduction is likely. However, this reduction would only serve to delay the timing of investments in desulfurization equipment. In this respect, the projections made below probably overestimate the number of refineries which must invest in the near term to some degree.

In most cases, the overall costs of desulfurization equipment is minimized when its construction is conducted in one step (enabling the production of 30 ppm gasoline), as opposed to a two step process involving some intermediate sulfur level. Thus, we also assumed that if a refinery had to install new equipment to meet a particular sulfur standard, it built equipment sufficient to comply with the 30 ppm standard and 80 ppm cap. There are some situations, particularly those involving higher baseline sulfur levels, where the equipment needed to meet the final 30 ppm standard involves more than one desulfurizing unit. In this case, it may be possible to install the major unit prior to October 1, 2003 and meet the 2004 requirements and delay the other unit(s) until 2005 or 2006. This possibility was not accounted for here.

Sulfur group #4 in Table IV-14 shows that 39 refineries have current sulfur levels above 300 ppm. These refineries must reduce their gasoline sulfur levels to 300 ppm or less by October 1, 2003, due to the per gallon cap taking effect at that time. In accordance with the above premises, the 39 refineries in this group would require fully operational desulfurization equipment by this date. In fact, this is likely an overestimation. Some of the refineries in this group are within 10-15 ppm of the 300 ppm cap. It is likely that these refineries could reduce their sulfur levels by a few ppm without installing new equipment. However, regular grade gasoline tends to contain more sulfur than premium grade. Meeting a per gallon cap with regular grade gasoline may require the refinery average sulfur level to be somewhat below 300 ppm. Also, refineries do not produce identical gasoline each day; there is some variation in the quality of gasoline produced throughout the year. Since the 300 ppm cap applies to each and every batch

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of gasoline produced, this variation also requires that the average sulfur level be below 300 ppm.

This implies that some of the refineries in Group #3 would also have install desulfurization units to meet the 300 ppm cap. However, this ignores the possibility of sulfur reductions from operational refining modifications and reducing historic variation in gasoline quality given an economic incentive to do so. We project that these more modest modifications, along with improved blending techniques, would be sufficient for those refineries currently near the 300 ppm level to produce regular and premium grades of gasoline under the 300 ppm cap.

Thus, we project that 39 desulfurization units would have to be installed and operating prior to October 1, 2003. We also project that six of these units would be installed by mid-2002, 12 would be installed by January 1, 2003 and the remaining 21 units would be installed by October 1, 2003. The projection of the 6 early units reflects the fact that technology vendors wishing to license their technology to refiners will need to demonstrate this technology early in the process. EPA projects that at least six technologies will be competing in this timeframe. We are already aware of at least three plants which will be in operation during 2000 or early 2001, two CDTech units and one Mobil Octgain unit. Assuming that EPA issues its final Tier 2/Sulfur rule by the end of 1999, mid-2002 is exactly 30 months later, which is generally the minimum time EPA projects for installing such equipment. Of course, given the commercial purposes for constructing and operating this equipment, plans could begin well before the final rule is signed, as indicated by the two projects mentioned above.

The 12/21 split between the 2003 and 2004 units was based on the premise that some refiners would want to generate credits for use in their other refineries in 2004 and 2005 or for sale to other refiners. We also expect that refiners, process design firms, and construction firms would want to spread out the design and construction of this new equipment as much as possible. Installing this new equipment within 36 months of the final rule (i.e., by January 1, 2003) is certainly feasible, given the projections made in the previous section. Thus, EPA believes that there would be an economic incentive to begin construction at some refineries sooner than at others.

Using the same assumptions, those refineries with current sulfur levels between 180 and 300 ppm would have to install equipment for use by January 1, 2005. As shown in Table IV-14, this group includes 25 refineries. Finally, the 30 ppm standard effective in 2006 would require another 33 refineries to install desulfurization equipment. Ten refineries out of the total of 107 refineries located in the U.S. outside of California already have sufficiently low sulfur levels to avoid the need for new equipment.

Table IV-15 shows the effect of the phase-in of this new equipment on average sulfur levels in the non-California U.S. gasoline pool. As can be seen, pool average sulfur levels in 2004 and 2005 are 105 and 49 ppm, respectively, well below the proposed 120 and 90 ppm corporate average standards. Thus, no additional controls should be required to meet these average standards if sufficient credits are available either from within the corporation or on the open market. This conclusion presumes that refineries with current sulfur levels in between the



corporate average standard and the per gallon cap (e.g., 120-300 ppm in 2004) are a part of a corporation which has another refinery at 30 ppm, so that its actual corporate average sulfur level is below 120 or 90 ppm, as applicable, since these standards must be met without the use of credits.

**Table IV-15. Effect of Phase-In of Sulfur Control to Meet Sulfur Caps in 2004 and 2005**

	2000	2001	2002	2003	2004	2005	2006
Pool Average Sulfur Level (ppm)	312	312	296	216	105	49	30
Number of Refineries Building Sulfur Units	0	0	6 *	12	21	28	30
Percentage Controlled to 30 ppm	0	0	7%	22%	47%	73%	100% **
Credits (ppm over the entire U.S. gasoline pool for an entire year)							
Credits Generated from Winter RFG	20	20	20	20	0	0	0
Credits Generated from Sulfur Units	0	0	16	96	0	0	0
Credits Used to Allow Sale of >30 ppm Gasoline	0	0	0	0	-75	-19	0
Cumulative Credit Balance	+20	+40	+76	+192	+117	+98	+98

\* Units only operate during second half of 2002.

\*\* Includes 2% of fuel which is currently below 40 ppm sulfur.

This table also shows the sulfur credits generated and used by refineries between 2002 and 2006. As can be seen, 112 ppm of credits were generated by the 18 units operating before January 1, 2004. This amount is greater than the 94 ppm of credits which are needed by the 58 refineries which did not begin operating sulfur units until 2005 or 2006.

Table IV-15 also shows a series of 20 ppm credits under the heading of wintertime RFG. The proposed credit provisions allow winter RFG to generate sulfur credits if its sulfur level is

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below the individual refinery's baseline sulfur level, which on average is 312 ppm. Summer RFG is expected to contain 150 ppm sulfur or less. EPA projects that the cost of extending this control (or rebinding) to the winter months would be minimal and that refiners would likely choose to generate credits in this way. The 20 ppm per year of credits represents the difference between the U.S. pool average sulfur level (312 ppm) and the 150 ppm level (difference of 162 ppm), multiplied by a factor of one-half, since only winter fuel would receive the credit and by a factor of 0.25, since RFG is roughly 25 percent of the non-California gasoline market.

Given this expectation of significant RFG-related credits, EPA projects that a significant excess of credits would be available. This analysis assumes that all credits which are generated are either used within a corporation or are put up for sale on the open market. This may not occur in all cases. However, this analysis indicates that only about half of the credits expected to be generated are actually needed to allow refineries with current sulfur levels below either 300 ppm or 180 ppm to delay installation of desulfurization units until 2005 or 2006, respectively. It is also possible that many more credits would be available, if many refineries use operational techniques to reduce sulfur to levels below the 150 ppm trigger level before the time that they install desulfurization units. On the other hand, fewer credits would be available if refineries adopt an alternative schedule to phase-in desulfurization capacity (because of capital constraints or site specific factors affecting individual control decisions) than the schedule posited by this analysis. As noted above, for example, some refineries may be close enough to the 300 ppm cap to be able to reduce their sulfur levels to meet the cap without installing new equipment. There may also be cases where refineries have such high baseline sulfur levels that more than one desulfurization unit would be required to produce 30 ppm sulfur gasoline on average. In these cases a decision to phase-in these units rather than installing 30 ppm technology initially would reduce the number of credits generated early. However, even if fewer refineries install desulfurization equipment to generate early credits than our analysis assumed, we believe there will be sufficient credits generated from winter RFG and from early installation of some 30 ppm technology to fully cover the credits needed by the industry.

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